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A STUDY OF WAVES IN THE EASTERLIES

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A STUDY OF WAVES IN THE EASTERLIES

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INTRODUCTION

1. Scope and Purpose of Report.

Until quite recently, weather analysis in the tropics remained almost wholly neglected. Except on the subject of hurricanes, only a few reports concerning tropical synoptic systems have appeared, and nearly all of these are of very recent date. The following is a list of published papers dealing directly with the subject of waves in the easterlies:

Bennot, Carlos - "Notes on Waves in the Easterlies", 9th Weather Region Forecasters Information File, 31 May 1944.
Dunn, Gordon E. - "Cyclogenesis in the Tropical Atlantic", Bulletin of the American Meteorological Society, Vol. XXI, June 1940.
Regula, H. - "Druckschwankungen und Tornados an der Westküste von Afrika", Annalen der Hydrographie, Vol. 64, 1936.
Riehl, H. - Waves in the Easterlies and the Polar Front in the Tropics, Miscellaneous Report No. 17, Department of Meteorology, Univ. of Chicago, January 1945.

In addition, it should be mentioned that a description of the waves is contained in a recent training manual on "Tropical Meteorology" of the U. S. Air Force [redacted] and the new "Handbook of Meteorology," [redacted] edited by Berry, Bollay and Beers (McGraw-Hill, 1945) [redacted] Several reports of Rev. Chas. E. Deppermann, Assistant Director, Philippine Weather Bureau, also have a bearing on the subject as do certain parts of the literature on tropical storms.

The papers cited above have of course not been able to treat all phases of the subject exhaustively. Dunn, who may be described as the first writer on allobaric systems short of hurricanes moving from east to west in the western Atlantic, was interested primarily in hurricane forecasting and dealt with the waves because many hurricanes of the western Atlantic are derived from these systems. Riehl's studies at the Institute of Tropical Meteorology, University of Chicago, are the first attempt to describe the structure of the waves. In the initial portions of his work he was concerned to a considerable degree with the problems presented by the analysis of the waves. This emphasis was reasonable in view of the fact that the entire subject was so uncertain until recently that many meteorologists remained long unconvinced that the waves actually exist.

A logical continuation of the preceding studies calls for two distinct phases of investigation:

a) An attempt must be made to ascertain to what extent the current theories of structure, displacement, and weather distribution are verified in practice. Theory, for example, calls for a definite pattern of weather distribution about a steady state wave. Forecasters however have observed that at times there are certain departures. A statistical study of a large number of waves should bring out the characteristics of different types of waves and furnish a picture both of average conditions and of deviations from such an average.

b) The problem of origin, maintenance, intensification, and dissipation must be further investigated. Their solution would be of great forecasting significance, and also afford a more complete understanding of the nature of the waves.

The report deals with the problems mainly in a synoptic and statistical manner. This does not mean there are no theoretical ideas presented, but only that they are presented in synoptic terms and by reference to synoptic patterns. Nor does it mean that there is no proof or verification of these ideas except by illustrative examples, but only that proof is statistical rather than dynamic or physical. Although the report is based mainly on data of the western Atlantic, most of the ideas presented should also apply to all other areas, where waves in the easterlies are found.

2. Material and Examples Used.

The data for this study were obtained from the surface and upper air data for June to October, 1944 as collected and disseminated by the AAF Weather Service in the Caribbean and from the historical weather maps published by the United States Weather Bureau.

The sixteen strongest waves that could be found in the period June-October, 1944 were selected for study in detail.[1] These waves were sufficiently intense, so that their positions could be located on each map with reasonable certainty and accuracy. Other weaker

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[1] Their dates are as follows:- 28 Jun-1 Jul, 3-10 Jul, 8-13 Jul, 9-16 Jul, 15-17 Jul, 24-29 Jul, 26 Jul-3 Aug, 31 Jul-2 Aug, 13-22 Aug, 15-24 Aug, 1-10 Sep, 13-21 Sep, 17-27 Sep, 5-9 Oct, 13-15 Oct, 16-20 Oct.
For certain additional purposes, mainly in the study of dissipation six additional waves were selected, namely 22-26 Jun, 1-4 Aug, 4-8 Aug, 10-15 Aug, 26-29 Aug, 23-26 Oct.

waves were ignored, not only because probably they were not important weather producers, but also because of the difficulty of finding them, verifying their positions, and tracing their movement with good continuity.

On the northern hemisphere surface charts, the months of July-September, 1924-1938, were examined. Certain obstacles were immediately apparent. The maps are on a very small scale; the reports spotted are not complete synoptic models; there is only one map (1300Z) for each day, which hinders the continuity. Finally, no upper air data at all were available at the time of the study. On account of these obstacles, only the strongest waves could be used, many of which developed a closed circulation at some stage. Forty- [redacted] five of these pronounced waves were selected, an average of one a month.[2]

It is felt that the difficulties mentioned above are more than compensated for by the presence of the great number of Atlantic ship reports, whose surface winds should be much more representative than those of land stations, as well as daily reports from Europe, Africa, Iceland, Greenland, Bermuda, the Cape Verde Islands, Madeira, the Azores, and the Canary Islands. The availability of these data

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[2] Their dates in the Western Atlantic and Caribbean:- 12-18 Aug 1924, 17-25 Aug 1924, 27 Aug-3 Sep 1924, 5-14 Sep 1924, 11-17 Sep 1924, 10-18 Sep 1925, 22-28 Jul 1926, 3-9 Aug 1926, 12-18 Aug 1926, 17-25 Aug 1926, 20-24 Aug 1927, 7-14 Aug 1928, 11-17 Sep 1928, 18-25 Aug 1929, 7-16 Sep 1929, 16-24 Jul 1930, 3-12 Aug 1930, 22-27

permits a much more accurate Atlantic surface analysis than could possibly be made from current war-time maps even with the aid of upper air data. For the chapters on origin, maintenance, intensification, and dissipation, the Atlantic material is considered essential; and in these chapters the conclusions are based mainly on the historical maps.

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2 (cont.)

Aug 1930, 31 Aug-7 Sep 1930, 3-12 Jul 1931, 9-18 Aug 1931, 29 Aug-9 Sep 1931, 9-15 Sep 1931, 24-31 Aug 1932, 28 Aug-9 Sep 1932, 23 Sep-3 Oct 1932, 13-22 Jul 1933, 24 Jul-5 Aug 1933, 12-21 Aug 1933, 17-23 Aug 1933, 8-15 Sep 1933, 20-26 Aug 1934, 9-15 Sep 1934, 16-22 Sep 1934, 16-23 Aug 1935, 26 Aug-4 Sep 1935, 20-29 Sep 1935, 23-31 Jul 1936, 10-18 Sep 1936, 16-22 Sep 1936, 23-31 Aug 1937, 21 Sep-3 Oct 1937, 9-14 Aug 1938, 16-20 Sep 1938. Numerous other waves also were found which were occasionally used for verification purposes, though they were either too weak or their positions and movement too uncertain to be included in the list.

CHAPTER I

ORIGIN

A knowledge of the process of formation of waves in the easterlies is necessary for an understanding of their nature. Also one eventual step in long range forecasting of these waves must be the ability to predict their generation.

Four plausible methods of formation are indicated below although it is by no means suggested that these constitute the only ways in which waves may develop:

<u>a</u>) Formation in the deep undisturbed easterlies on the equatorial periphery of the subtropical highs.

<u>b</u>) Transformation and retrogression of a stagnating extratropical trough.

<u>c</u>) Emission from an extratropical trough as a separate entity.

<u>d</u>) Formation on the equatorial front.

1. <u>Formation in Undisturbed Easterly Flow</u>

Some meteorologists have suggested that a deep easterly current in itself may cause the formation of waves. It is observed that waves do occur when the trades are strongest and in the season when they are generally prevalent over a wide latitudinal belt. In order to ascertain whether this means that the deep easterlies can actually develop waves without the necessity of additional factors, 1380 historical maps were examined to find periods of at least three days when a substantial high persisted over western Europe joining the main oceanic high (Fig. 1). In such a situation no North Atlantic trough can extend into the tropics near Africa or over the central Atlantic.

Ten ideal cases with strong, undisturbed easterly flow were found, mostly in July, when the oceanic high is most intense.[1] The Caribbean area was then examined five to ten days later for evidence of disturbances, and in not one of these ten instances were there any signs of a wave.

The above cases, as well as the lack of a logical explanation of the hypothesis, point very strongly to the conclusion that deep easterlies in themselves are not sufficient to form waves and indicate that outside influences are essential for their generation.

2. Development from an Extratropical Trough.

What then is necessary in addition to the existence of the easterlies themselves for the formation of waves? One logical explanation would appear to be that these waves have as their source temperate latitude troughs that extend far into the tropics. This is not to say that they are separate phenomena which emerge from such troughs, but rather that they represent a later stage in the evolution of waves in the polar westerlies. Under certain conditions, the latter stagnate and their tropical extensions eventually begin to

[1] Examples of such periods are 15-20 Aug 1925, 19-24 Jul 1928, 25-28 Jul 1929, 30 Jun-4 Jul 1934, and 11-18 Jul 1935.

move westward in the tropical current.[2]

Such a development is most likely to occur, if a wave trough in the westerlies stagnates for a considerable period of time because the transformation into a wave in the easterlies coupled with retrogression is certainly not instantaneous. The sequence of events seemingly necessary for such an evolution is discussed below.

a) <u>Stagnation of troughs:</u> The projection of a temperate latitude trough of the middle troposphere into the tropics commonly is associated with the occurrence of an extratropical low farther north. As long as this trough persists with sufficient strength between two subtropical highs, a trough in the easterlies is found south of the surface axis of the highs. This trough represents a reflection of the upper trough in the westerlies in the absence of any compensating effect in the layer underneath.

The wave troughs in the westerlies move eastward across the ocean, when the high to their east dissipates or retreats eastward. They will slow down, however, or they may be checked altogether if a strong subtropical high blocks their advance and does not give way. In addition, the eastward movement is halted occasionally by stagnation of the extratropical low itself. This occurs mainly, if a

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[2]This theory previously has been mentioned by Dunn (3) and Riehl (6). Riehl expresses doubt, however, that polar troughs account for the formation of all waves, since such troughs seldom extend deep into the tropics in summer, the principal wave season.

deep, occluded system is involved; and the trough that extends southward then will tend to be very intense containing a predominantly north-south flow.

b) Bisection of trough: In order to establish a situation favorable for westward motion of the trough in the lower latitudes, a separation from the parent low is necessary. This separation results through bisection of the trough that extends from the polar zone into the tropics and may occur in two ways:

First, the extratropical low, steered by the subtropical high, may move to the northeast of the high. In this event the westerly trough in higher latitudes, moving toward the east, becomes detached from its tropical extension, which is blocked by the high to its northeast and hence stagnates.[3] Simultaneously, the high west of the low will tend to merge with the subtropical high to the east (Figs. 2,3). This merger may be caused by the eastward advance of the western high, by the southwestward movement of the subtropical high, or by both. Evidence indicates that the southwestward movement of the subtropical high, often associated with intensification, takes place most frequently.

This merger of the highs brings on strenghtening of the trades. Likewise the movement of the parent low eastward from the area restores and deepens the upper-level easterlies. These factors are the motivating forces which initiate westward movement of the re-

[3] cf. also Riehl (8)

flected trough. As the subtropical high continues shifting westward, it assures the maintenance of the pressure and flow pattern necessary for westward movement of what we may now call the wave in the easterlies.

Secondly, an eastward advance of a subtropical high may constitute the motivating force that produces the bisection of the polar trough. This situation is aptly shown in the case of lows which deepen near the English coast and move slowly northward, northeastward or even northwestward. Here we find a deep trough situated east of the Azores high. As the parent low moves northward, the high protrudes eastward through the trough in the subtropics and institutes a strong trade current across the southern part of the trough. This type of bisection is often accomplished very rapidly and the high appears to suddenly encompass the trough with its circulation. (Figs. 4-5).

c) Evidence: The proposed theory of origin of waves in the easterlies from extratropical troughs does not presuppose any fixed source region. Presumably waves may originate during any season at any place where the situation is favorable for the unfolding of one of the sequences just described. However, strong waves seldom originate in the western Atlantic or in the Caribbean; and indeed no good examples of formation in those regions were found on the 1924-38 historical maps. Thus the central and eastern Atlantic remain as the principal regions of the North Atlantic for wave generation.[4]

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[4]Waves may also form in the western part of Central Africa or even farther east, and move westward into the Atlantic.

To test the theory, the 45 waves selected from the historical maps were extrapolated back across the Atlantic to the African coast from the position where they were first definitely located, occasionally as far east as 30°W. Long. For the extrapolation, the average daily displacement in the Caribbean was used. All intervening maps were then inspected for troughs to the north which might give a clue regarding the genesis of the waves. Later the process was reversed, and the maps were examined for the presence of intense extratropical troughs. When such conditions were found, the next eight or ten maps were inspected to see if a wave entered the Caribbean during that interval, whose origin might be attributed to them. The results of these studies are given separately below.

<u>Eastern Atlantic</u>: The northeastern Atlantic, where the semi-permanent Icelandic low is located, has long been known as a region of great cyclonic activity. Extratropical lows entering this region from the west frequently decelerate in the area between England and Iceland. Normally the upper trough associated with such a low does not extend far equatorward in the mid-Atlantic. As soon as the low slows down and deepens after passing the center of the oceanic high to the south, however, the trough begins to penetrate into the tropics. This is the phenomenon known as the "induced trough." Its occurrence indicates that the extreme eastern Atlantic is favorable source region for waves in the easterlies, but the significance of each individual trough tends to be minimized due to the frequency of this situation.

Forty of the 45 waves appeared to be of African or East Atlantic origin and could be extrapolated back into this area. In the case of all but six of these, a trough in the westerlies extended from western Europe into the tropics near the African coast about the time when formation should have taken place. This, however, was not as useful a criterion as it might at first appear, since a random sampling of all the maps without reference to waves in the easterlies showed that a trough existed in this area nearly half the time.

The next step then, was to examine the characteristics of the polar troughs themselves, chiefly as to intensity and speed. Only the more intense troughs could be expected to extend far enough into the tropics to generate any tropical disturbances while fast-moving or accelerating troughs were seldom deep enough or extended sufficiently far southward. Consequently, it was assumed that only troughs connected with deep or slow-moving lows would be suitable for wave formation.

Application of this criterion yielded encouraging results. The statistical central pressure of the Icelandic low is about 1008 mb in July and 995 mb in January. On the maps that correspond to the time when the waves in the easterlies should have formed--all summer maps-- the central pressure was 995 mb or lower in half of the 32 cases in which measurements could be made and 1000 mb or lower in 25 out of the 32 examples. In only two of the 32 cases was the central pressure over 1005 mb. In the calculations, care was taken to exclude situations in which the Icelandic low was far north of its mean position with an arm of the Azores high over Europe to the south of the low. In these cases any great southward extension of the upper trough was blocked, regardless of depth and degree of stagnation of the parent low.

The same test was then applied on a negative basis as follows: From the 1380 maps, the deepest Icelandic lows were taken, defined as 985 mb or lower at center and also all the slowest-moving lows defined as persisting three or more days with no apparent motion of more than two degrees lat. Many of these lows had both characteristics since normally deep lows move rather slowly. Whenever such conditions were found, the maps from five to ten days later were next inspected to determine whether or not a wave arrived in the western Atlantic or Caribbean whose origin could be attributed to the trough associated with the low. In the case of deep lows, such waves appeared in 23 out of 29 cases,[5] and in the case of slow-moving or stationary lows, waves appeared in fifteen out of eighteen cases.[6] This is rather strong statistical evidence in support of the theory.

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[5] Examples are 1-18 Sep 1925, 17-27 Sep 1927, 2-16 Aug 1930, 14-30 Sep 1933, and 12-27 Sep 1935.

[6] Examples are 6-15 Sep 1924, 1-18 Sep 1925, 25 Aug-10 Sep 1929, 2-16 Aug 1930, and 12-27 Sep 1935.

Figures 4 and 5 illustrate the formation of a wave in the eastern Atlantic.

Central Atlantic: Waves in the easterlies may form in mid-Atlantic from a trough that is blocked by a strong Azores high. In order to determine if waves developed from such troughs, the 45 historical waves were again extrapolated back through the Atlantic using the rate of movement first observed in the Caribbean. In fully half of the cases there was at least one polar trough in the Central or West-Central Atlantic past which the wave must have moved if it had formed in the eastern Atlantic. In a few cases there were two such troughs. Most of them appeared in late August or in September, since in July and early August the oceanic high was predominantly single celled and too extensive to permit penetration of a trough in mid-ocean.

In many instances it was doubtful whether a wave formed from the mid-Atlantic trough or started farther east moving past the trough in its westward course. In some situations, however, the evidence was conclusive that the origin itself took place in mid-Atlantic, particularly when there was a noticeable lack of troughs in the eastern Atlantic. In those instances, the mid-Atlantic trough was initially flanked by two distinct anticyclones which eventually merged. This merger indicated bisection of the trough and indeed waves appeared in the Lesser Antilles after the proper period.[7] (compare Figs. 2,3). Careful analysis indicated that there was no possibility that these waves may have formed between the Central Atlantic trough and the Lesser Antilles before the merger of the highs was accomplished.

3. Emission from an Extratropical Trough

Another possible method of formation, closely related to that just mentioned, also involves the polar trough. The substance of this hypothesis is that waves form along the trough, but move westward from it as separate entities while the parent trough retains its identity.[8] The waves are considered to be primarily derived through impulses from the higher latitudes. The equatorward parts of small troughs in the westerlies that approach the stagnant broad scale troughs from the west in the higher latitudes, are carried first southward and later southwestward and westward in the broad current west of the stagnant trough, and thus eventually emerge as waves in the easterlies.

The hypothesis was tested through examination of periods when a deep trough stagnated in the mid-Atlantic for several days. In none of these cases did a wave in the easterlies appear in the Caribbean before the trough dissipated, began moving eastward, or receded westward.[9]

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[7] Examples are 4-8 Aug 1931, 3-10 Sep 1929, 5-12 Sep 1933, and 19-30 Aug 1935.

[8] Riehl (6) apparently considers this hypothesis plausible when he says "There is some reason to believe that, wherever a trough of great latitudinal extent remains nearly stationary for several days, waves originate in the easterlies in the region of the equatorward parts of this trough and are carried westward." He further expands on the hypothesis in a more recent report (8).

[9] Examples of such periods are 17-23 Jul 1933, 3-7 Sep 1933.

This would appear to be conclusive evidence that polar troughs do not emit waves while they maintain their identity as separate and distinct troughs in the tropics. The conclusion is that whenever a deep and stagnant trough lies off the Lesser Antilles or in the mid-Atlantic, a forecaster can confidently state that, so long as the trough remains stationary, no wave will move into the area to the west.

4. Formation on Equatorial Front

a) Theory: Much has been written on the possibility that some, if not all, tropical storms form on the equatorial trough. Whatever has been said on this subject might also apply to waves in the easterlies, as long as it is compatible with the requirement that the zone of convergence lie along a line rather than in a circle. No theory of development of a disturbance from the mere expansion and intensification of a single thundercloud or local center of convection could account for the waves. Likewise no theory of an occluded or triple point low could explain them, nor any theory of an open frontal wave with a closed circulation about it. A more promising possibility arises in situations where a stagnant polar trough lies to the north of the equatorial front. At such a time the front moves farthest north and the combined action of the trough

9 (cont.) 18-22 Aug 1935, 24 Sep-4 Oct 1944, and 8-13 Oct 1944.

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and the front may generate a wave in the easterlies.

b) Evidence: The eastward extrapolation of the waves back to the African coast indicate that whenever waves were in that area the equatorial trough—or the northern limit of winds with a southerly component—often appeared to be located farther to the north than usual. To test this, the August and September maps for six years were checked to see if any surface winds north of latitude 15°N in Africa, the Cape Verdes or ships thereabouts had a wind with a southerly component (anywhere from eastsoutheast to west).[10] At least one such wind occurred on 45 maps, i.e. 12% of the time. Next 27 tropical disturbances entering the Caribbean from the east between 1924 and 1938 which appeared to have formed in the eastern Atlantic were extrapolated back to Africa. At the time when these wave should have been in the Cape Verde area, if at all, southerly winds occurred there in the case of eleven of the 27 storms.

Next this process was reversed by taking all the days when south winds occurred in the Cape Verde region in order to determine how frequently a wave or hurricane entered the Caribbean five to nine days later. In the twelve months tested there were 26 periods of one or more days in which south winds occurred. Twelve times only did a wave or storm enter the Caribbean five to nine days

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10 In summer, winds with a south component in that region may often be taken as an indication that the equatorial trough is to the north.

later.[11]

c) Conclusion: The foregoing does not imply that in each case when the winds had a southerly component it was conclusively determined that the equatorial front was north of 15°N. lat. or that this caused the south wind or formed the wave. It may be that the wave had already formed and the south wind only demonstrated that the wave was west of the station and strong enough to change the usual north or northeast wind into a southerly one. But whether the area of and just north of the equatorial trough is the source, the source region, or neither, the significant fact remains that this is the area which should first be examined, and the area where most often evidence of a wave will first appear. If a wave can be so found, the inability to forecast its actual genesis is not a great detriment to the forecaster.

Thus, it is not suggested that the Cape Verde and Equatorial Africa wind analysis be used to verify the origin or even the source region of the wave, but only to identify the existence of the wave at an early stage when it is still in the eastern Atlantic. Then by proper prognostication of its movement, its arrival in the Caribbean or Guiana area may be forecast from four to ten days in advance. Finally it should be cautioned that the correlation shown above was not satisfactory enough to recommend the use of any strict fore-

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11 Examples are the maps for 13-21 Aug 1927, 6-12 Sep 1928, 15-30 Aug 1932, 17-31 Aug 1935, 2-22 Sep 1936 (two storms), and 1-12 Aug 1938.

casting rule based on the Cape Verde winds. Rather these winds should serve as a warning or notice to the forecaster to be on the lookout for a wave a few days later in the area farther west where sufficient data are present to locate it definitely.

CHAPTER II

STRUCTURE

The following discussion concentrates mainly on the problem of how the models of the wave structure (6) were verified in the case of the sixteen 1944 waves. Special emphasis was given to the horizontal and vertical orientation, the wind patterns and the pressure and temperature distribution about the waves. It should be kept in mind that in theoretical approaches by Riehl and others, steady state conditions were assumed. In the data used here, however, accelerating, decelerating, deepening, and filling waves are considered as well as steady state waves.

1. Horizontal Orientation

Since the stations of the Antilles chain lie roughly normal to most waves, it is difficult to ascertain the exact orientation of a wave trough, once it has passed the Lesser Antilles. Only Curacao, N.W.I. is situated far enough south to serve as a checking point.[1] If the position of a wave can be located with sufficient accuracy in the Antilles at the time it passes Curacao, its horizontal orientation can be determined fairly successfully. Twelve of the sixteen waves passed Curacao with sufficient evidence to ascertain

[1] Swan Island, Grand Cayman, Jamaica and the Bahamas are also situated off the main island chain. However, in 1944 too few waves progressed far enough west to warrant statistical computations there.

the time of passage to within six hours (in a few cases 12 hours). The mean orientation of the trough lines was north-northeast—south-southwest and the extreme deviations from this mean were only north-south, and northeast-southwest.

On the average, therefore, the wave troughs were oriented about normal to the mean flow between 1000 and 15000 feet at Puerto Rico in summer. According to Stone (2), San Juan resultant winds for these levels lie between 95° and 130°. In addition, the orientation of the wave troughs tended toward north-south when the mean flow across the trough was more easterly, with a windshift from northeast to southeast with passage. Conversely, when the general flow was more southeasterly, the wave trough was located more northeast-southwest. These data corroborate the suggestion, that the disturbances should be considered as transverse waves in the easterly current. They also suggest that the wave troughs gradually assume an orientation more nearly east-west, as they pass from the eastern into the western Caribbean, where the mean flow is more southerly.

2. Slope with Height

Waves in the easterlies generally slope eastward with elevation, unless they are undergoing transformation under the influence of extra-tropical systems. According to Riehl (6) their axes are nearly vertical up to 5000 to 8000 feet and slope eastward above that level. To determine the slope as closely as possible, computations were made from time sections of the upper winds at San Juan. This method is not entirely satisfactory. At the higher levels, there may be an error amounting to twelve hours in the determination of the time of passage. Moreover, use of the time sections for determining slope presupposes a constant speed of the waves, which in individual cases of course is not always true. Indeed, in regions where the waves tend to stagnate, the method is inapplicable. At San Juan, however, where the waves passed more or less regularly during 1944, the figures should give a good indication regarding the average slope of waves in the easterlies near Puerto Rico.

The average lag between wave passage at the ground and at 40,000 feet was 16 hours. The average speed of the waves at San Juan was 17 m.p.h. near the surface. Thus the slope with height was approximately 1:35, or about half the slope of an average temperate-zone cold front. Although Riehl (6) gives no figures, his model shows a slope of the same order of magnitude.

3. Vertical Extent

The installation of rawins at San Juan and Cayenne early in 1944 provided an opportunity to study flow and flow changes at high levels which could not be ascertained in previous years. Rawin observations were taken two to four times daily and information to 30000 and 40000 feet was obtained with great consistency. These records indicated that the height to which the windshifts with the passage of waves in the easterlies extended was often enormous, though in most cases the turning was most marked between 10000 and 20000 feet. At San Juan, a shift of over 80° took place at 30000 feet in eight out of nine cases where winds to that level were available. Only once was there a lack of evidence of wave passage at this level. At 40000 feet, a shift of 80° or more was again in evidence in seven of the nine instances cited. In another instance, the rawin extended to only 35000 feet. At that level a good wind shift was in evidence.

In view of these more recent data, Riehl's statement (6) that most waves do not show changes in the high troposphere should be modified. It should, however, not be overlooked that the waves selected for study during 1944 were the most intense ones of the season, and that weaker waves were omitted. Perhaps it is best to state that at least the intense waves may extend to the sub-stratosphere or higher.

4. Wind Distribution

Figure 6 represents a vertical cross-section of the winds through a wave in the easterlies. In addition, the height of the moist layer is given by the dotted line. In 1944, the wind normal to the troughs of the intense waves was considerably greater to the rear of the troughs than ahead in the lower troposphere. This indicates convergence of the current in which the waves were embedded toward the wave troughs from the east. As shown in section 1 of this chapter, this current usually travelled from ESE. Its speed frequently exceeded the speed of the waves in the low levels, especially near 5000 feet, so that in the lowest layers air moved westward through the waves. There was, however, a decrease of the motion normal to the wave troughs with increasing height, and at 30000 feet and higher even a reversal of direction relative to the earth. Thus, in the middle and upper troposphere, the wave troughs generally travelled faster than the air, so that the air moved eastward through the troughs, occasionally at speeds in excess of 20 m.p.h. A qualitative application of Rossby's vorticity theorem (9) shows that, below the base of the westerlies, all layers that move considerably slower than the waves should converge while ahead of the wave trough, and diverge once the trough has overtaken and passed them. Thus the low level divergence gives way to convergence with height ahead of the troughs and to their rear low level convergence is succeeded by upper divergence. This description agrees well with that given by Riehl (6).

There is, however, evidence to suspect the presence of additional layers of alternating convergence and divergence with increasing height. According to Riehl (6) the wind shift weakens above 20000 feet. While this is generally true, rawin data, not available in previous years, indicate that in the upper troposphere the windshift again increases in the case of pronounced waves as stated above. Wind vectors showing the difference in the meridional flow component at several levels ahead and behind the wave troughs were computed for twelve 1944 waves. The difference was greatest between 5000 and 15000 feet; lessened between 20000 and 30000 feet; and increased again above that level. At 40000 feet the shift was greater than at 20000 feet, and considerably greater than in the layer from 25000 to 35000 feet. If the preceding data may be interpreted to indicate alternate weakening and strengthening of the wave-troughs with height, then it appears reasonable to conclude that there are several alternating layers of convergence and divergence with height. And while one reversal takes place between 15000 and 20000 feet, another one occurs between 30000 and 35000 feet which is near the average height of the base of the westerlies. The observation of such layers agrees well with recent, as yet unpublished theoretical investigations by Professor C.-G. Rossby regarding the distribution of convergence and divergence with height in atmospheric waves.

The preceding discussion was based on the change of the meridional flow component rather than the change of wind direction itself. The latter was greatest at the highest elevations. Between 5000 and 25000 feet there was an average shift of 60-70° in 12-24 hours, which increased to 100° at and above 35000 feet. This picture is produced primarily by the decrease of the easterly flow with height. At 30000 to 35000 feet and higher the zonal wind component tends to be very light, and small changes of the north and south components will produce large changes of the wind direction.

The direction therefore, does not yield an unbiased picture concerning the variation of the intensity of the waves with height, although the large changes at high levels provide an excellent tool for analysis. It is also of interest to note that except for the layer from 20000 to 25000 feet, the average northerly component ahead of the wave is fairly constant and increases upward becoming strongest at 30000 to 40000 feet. On the other hand, the southerly component behind the wave, very strong at 5000 feet decreases rapidly in the layer 15000 to 30000 feet and again strengthens above 30000 feet but not with intensity comparable to the northerly component ahead of the wave.

5. Height of the Base of the Westerlies

As emphasized in the chapter on maintenance, a deep easterly current is needed to maintain the waves. Thus the months with greatest wave frequency should be characterized by a high base of the westerlies. As computed from the San Juan rawins for 1944, the base averaged 10000 to 15000 feet in May, 20000 feet in June; 35000 to 40000 feet in July, August and October; 25,000 to 30000 feet in September, and 10000 to 15000 feet in November. Thus the seasonal march of the height of the base of the westerlies agrees quite well with the seasonal variation of wave frequency. Nevertheless, as stressed earlier, a lowering of the base will often accompany the passages of strong waves themselves. Bases averaging 31000 feet—nearly average height—preceded the passage of four well marked waves in the earlier part of the 1944 season. At the time of wave passage at the surface, and shortly thereafter, the base dropped sharply to an average height of only 17000 feet for the four waves, and then conditions returned quickly to normal. Since the troughline at high levels usually passes some hours after surface passage, it appears reasonable to conclude that the lowest westerlies are encountered along the troughline.

As suggested by Riehl (6), such a narrow band of low westerlies may be due to the presence of closed low centers aloft. The westerly winds, however, did not revert to easterly again in the four examples cited, but maintained themselves for the remainder of the ascents, to 50000 and even 60000 feet. Thus if the westerlies are caused by the presence of an upper low center, this center must extend to very great heights rather than persist only in the middle troposphere. If, however, the subtropical high were displaced south of San Juan in the high troposphere, the westerlies may be considered as part of the circumpolar westerlies.

There was a suggestive correlation between the lowering of the base of the westerlies and deepening. In several instances, where the lowering was most marked, a tropical disturbance formed within 24 hours. Moderate lowering was accompanied by slight deepening. Fast moving weak waves had the least effect on the base.[2] This observation corroborates the suggestions on tropical cyclogenesis presented by Riehl and Shafer (7) and what is said in this report concerning deepening of the waves. Evidently, however, a reversal of the lower easterlies to westerlies with height can serve as a warning of impending cyclogenesis only under these special circumstances, since this reversal is one of the outstanding and most persisting features of the non-hurricane season.

6. Pressure and Temperature

a) Pressure: For the study of pressure and temperature characteristics, the raobs of the following five Caribbean stations were used in addition to the surface observation: St. Lucia, B.W.I., Antigua, B.W.I., San Juan, Puerto Rico, Port au Prince, Haiti, and Batista Field, Cuba. From these soundings 24-hour pressure changes were obtained for the periods 0-12 hours and 12-24 hours before and after wave passage. 24-hour surface tendencies observed ahead and behind the wave troughs are given in Table 1. The figures indicate the number of occurrences.

[2] On 10 July 1944, the base of the westerlies fell from 23000 to 9000 feet at San Juan within nine hours after passage of a wave and a tropical disturbance formed on 11 July. A fast moving weak wave 12 July, was accompanied by only slight lowering from 30000 to 25000 feet. See also wave passages 29 June and 16 July when lowering averaged 9000 feet. In both cases the waves slowed down and deepened slightly.

TABLE 1

	Before passage		After passage	
	12-24 hrs.	0-12 hrs.	0-12 hrs.	12-24 hrs.
Falling tendency	40	47	11	9
Rising tendency	21	14	41	42
No change	4	2	9	11

The greatest fall in the period 12-24 hours before wave passage was 3.7 mb. The greatest fall in the period 0-12 hours before wave passage was 4.4 mb. The greatest rise found during the period 0-12 hours after passage was 3.5 mb and the greatest rise for the period 12-24 hours after passage was 6.2 mb. Extremes occurred with the waves that had closed centers.

The distribution of the changes agrees in trend with the descriptions of Dunn (3) and Riehl (6). Some of the deviations are due to the fact that the changes are not instantaneous. In a number of instances the true isallobaric field, especially with weak waves, was masked by the influence of higher latitude systems. In others it was affected by the interaction of two closely spaced waves.

Twenty four hour ~~?-hour~~ pressure changes aloft were obtained from time sections for the five stations listed above. Results at 10,000 and 20,000 feet only will be presented (Table 2) since the figures at still higher levels were too uncertain and inconclusive. This is in part due to scarcity of data and in part due to the necessity to assume an average slope of the wave troughs with height as well as a constant and equal displacement of the wave troughs at all heights.

TABLE 2

10,000 feet

	Before surface passage		After surface passage	
	12-24 hrs.	0-12 hrs.	0-12 hrs.	12-24 hrs.
Falling tendency	19	28	15	11
Rising tendency	5	8	24	31
No change	9	14	12	6

20,000 feet

	Before surface passage		After surface passage	
	12-24 hrs.	0-12 hrs.	0-12 hrs.	12-24 hrs.
Falling tendency	17	18	18	13
Rising tendency	6	18	13	22
No change	7	10	14	6

For the period 12-24 hours prior to surface passage, the greatest falls recorded were 4 mb. at 10,000 feet and 3 mb. at 20,000 feet. For the period 0-12 hours before passage the greatest falls were 4 mb. at 10,000 feet and 4 mb at 20,000 feet. For the period 12-24 hours after passage the greatest rises were 3 mb. at 10,000 feet and 4 mb at 20,000 feet. The results in general are fair.

It is difficult, however, to account for the increasing number of pressure rises 0-12 hours ahead of the wave troughs as compared with 12-24 hours ahead.

b) Temperature: Fifteen instances were available at San Juan for which 24-hour temperature changes could be computed from soundings less than 24-hours after surface passage. In cases where the raob in question was taken only a few hours after surface passage, the raob 12 hours later was also considered. This gave 20 soundings altogether.

The following 24-hour changes were noted. In eighteen cases there was a layer of cooling of at least 2°C, with base averaging 770 mb. (8000 feet), and top averaging approximately 460 mb. (21000 feet). The thickness and position of the layer varied. The base ranged from the surface to 570 mb. (15000 feet). The top was at or above the 540 mb. level (17000 feet) in all but two cases and below 400 mb. (25000 feet) except for two cases. In one instance there were two layers of cooling, one from 740 mb. to 570 mb. and one from 400 mb. to 200 mb. Eight times there was a layer of warming of 2°C or more, which was based four times at the surface, twice at 2000 feet, once at 3000 feet, and once at 4000 feet. The top of the layer of warming averaged 760 mb. (8500 feet) with extremes of 670 mb. (11100 feet) and 880 mb. (4000 feet).

In four of the five cases where two consecutive soundings could be analysed, the base of the layer of cooling lowered in the 12-hour interval between the two raobs and the amount of cooling increased. In the fifth case, no layer of cooling was in evidence on the first sounding, but appeared on the second. The lower layer of warming appeared on the first raob in four instances but disappeared in three instances on the second sounding. In the fourth case it weakened. The following extreme amounts of warming and cooling were obtained . The greatest cooling was 8°C. Once there was cooling of 6°C, once of 5°C, twice of 4°C and eight times of 3°C. The greatest warming was 5°C. Once there was warming of 4°C and three times warming of 3°C.

Thus, the following 24-hour temperature changes should ordinarily be observed with wave passage. At first there should be warming of 2-3°C at or near the surface and extending to 8000 feet, with a layer of cooling of approximately 3°C immediately above it. Twelve hours later the layer of warming should ordinarily have disappeared, or weakened considerably. The layer of cooling should have intensified with the base lowering to about 4000 feet and occasionally to the surface. This sequence of 24-hour changes suggests that the actual cooling begins immediately or soon after passage of the wave trough, while warming precedes it. It agrees well with the concept of low level divergence ahead of the wave troughs and convergence to their rear.

7. Height of the Moist Layer

The top of the moist layer has been defined frequently as that level where the relative humidity drops off rapidly with height to below 40%. The height of this level is on the average around 7000 feet to 8000 feet. Previous work concerning the effect of waves in the easterlies on the height of the moist layer indicates that it may lower to 5000 feet approximately 200 miles ahead of the wave; and that it rises rapidly about the time of wave passage, often exceeding 30000 feet. (6)

In order to see to what extent this picture verified, twelve waves between June and August of 1944 were examined for the effect of wave passage on the height of the moist layer at San Juan. In all instances except one, the height of the moist layer increased just after passage.

The average height of the moist layer during the period under consideration as obtained from 99 raobs, was 11,400 feet.[3] In the 24-hours preceding wave passage the moist layer averaged 11800 feet, or approximately the same as the general average. During the 24-hours after surface passage, the average depth was 18300 feet, representing an increase of about 50%. In 75% of the cases the the moist layer was deeper 12 to 24 hours after passage than 0-12

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[3] It is also of interest to note that the moist layer averaged 13700 feet (61 observations) when the mean wind between 1000 and 15000 feet blew from south to east, and only 7700 feet (38 observations) when it blew from north to east.

hours after passage.

Thus there was a pronounced rise of the top of the moist layer after surface passage, but the top was near the seasonal average before passage. It should be noted, however, that the waves were not all of the steady-state type. Some contained closed low centers while they were passing San Juan and others were deepening.

8. Conclusions

a) The horizontal orientation is nearly perpendicular to the mean flow between 1,000 to 15,000 feet, usually north-northeast—south-southwest.

b) The average slope of the waves with height approximates 1:35.

c) Strong waves are still well marked at 40,000 feet. There is, however, an intermediate region between 20,000 and 35,000 feet where they are noticeably weaker.

d) The most pronounced shifts with passage occur at 5,000 to 15,000 feet and again around 40,000 feet or higher.

e) Most waves are preceded by 24-hour pressure falls of 1-2 mb. on the surface and aloft, with subsequent rises of the same order of magnitude upon passage.

f) Shortly after passage, 24-hour temperature rises occur from the surface to approximately 8,000 feet with 24-hour cooling above;

greater 24-hour cooling that extends farther down follows 12-24 hours after passage.

g) Before wave passage the height of the moist layer is approximately normal, (12,000 feet). After passage, it rises to over 18,000 feet and attains its greatest height 12-24 hours after passage.

CHAPTER III

WEATHER DISTRIBUTION

Up to quite recently, efforts to treat the changing patterns of the daily weather in the tropics, apart from hurricanes, were very limited. Indeed, some officials of meteorological services in the tropics freely expressed the opinion that it was impossible to forecast the day to day changes of the weather. In the Atlantic region, Dunn (3) first considered variations in the height of the moist layer in relation to waves in the easterlies, under the name of moving allobaric systems. Frolow's discussion of a "cold front" passage at Martinique in 1941 (5), describes essentially the weather experienced with a reasonably strong wave. Riehl (6) and Bonnot (1) treat the theory of convergence and divergence around steady state waves and cite several observed cases.

In order to ascertain to what extent the theoretical patterns are borne out in practice, the weather distribution observed in connection with the 16 waves of the 1944 season was analysed in detail. Since several of these waves developed closed low centers, it also became necessary to refer to the weather patterns associated with tropical lows to some extent. The verification was carried out through an analysis of the distribution of the measured rainfall and with the use of an empirical formula which also includes cloudiness and which is described in the appendix to this chapter. All other information available from the synoptic and hourly observations was also utilized.

1. Average Distribution

At first a comparison was made between the average distribution as obtained from all waves of the 1944 season and the theoretical picture around a steady state wave, i.e. a wave that changes neither speed nor intensity. According to theory, the weather 8-24 hours before passage of a steady state wave trough should be considerably better than average, with damping of the diurnal convective activity and a minimum of precipitation. Then as the trough line passes at the surface, increased convection, showers, overcast skies, lines of cumulonimbus and middle cloud decks appear. The clearest skies should be found approximately 200 miles ahead of the wave trough and the greatest amount of bad weather approximately one-half this distance to the rear.

A statistical summary for all stations of the Antilles chain and the Guiana coast during the sixteen waves for 1944 gave .24 inches of rain in the thirty hours up to surface wave-trough passage and .48 inches of rainfall in the thirty hours after passage. At the same stations the average rainfall for a period of average diurnal weather, showed .15 inches rainfall in thirty hours. Therefore, on the average, weather ahead of a wave in the easterlies is considerably better than behind. However, compared to normal conditions, the weather before the wave is not especially fine. This statement should be qualified, however, by stating that all types of waves were included in the calculations, not merely steady state waves. The variance of weather distribution among the 16 waves themselves was great. Thus the average distribution does not help the forecaster greatly and a further breakdown of the 16 waves becomes necessary.

2. Weather Distribution in Relation to Speed of Waves.

A reasonably reliable wave characteristic that can be measured at an early stage is its rate of displacement. Once a wave is identified and properly located, successive charts will indicate its current rate of movement. In this discussion the speed of the wave (c) is used as the primary typing factor. It is more easily measured than, for instance, amplitude or intensity and for the most part there is a definite relationship between the speed of a wave and its intensity, and between changes of speed and changes of intensity. An additional consideration is the relation between the speed of each wave (c) and the average flow normal to the wave trough (U). Both (c) and (U) are here considered to be negative for motion from east to west.

Arbitrary limits of wave speed chosen for the classification are as follows:

18 m.p.h and above = fast
17.9 to 13.0 m.p.h.= moderate
Less than 13 m.p.h.= slow

As one might expect, very few waves fall into only one classification throughout their whole life history. Consequently, periods when the various waves maintained reasonably steady velocity were chosen and their weather distribution was studied during such intervals. Because only sixteen waves were available, each of the three groups contains very few cases. This is a serious drawback statistically. The following sections, therefore, should not be expected to present final results concerning the weather distribution with each type. They should rather be taken as an indication of what the final picture probably will show.

a) Fast moving waves: The rapidly moving waves of the 1944 season occurred primarily in the early part of summer.[1] These waves also did not produce tropical storms or closed circulation while maintaining high rates of displacement.

Rainfall and weather distribution show considerable deviation from the theoretical distribution around a steady state wave through which the wind blows from east to west. The average total precipitation for a period taken 30 hours before and 30 hours after surface trough passage was .78 inches. The amount before passage (.42 inches) exceeded slightly the total after passage (.36 inches). Thus the average six-hourly amount for five six hourly periods was .08

[1] 29-30 Jun, from St. Lucia to Puerto Rico; U = -15, C = -18.4 m.p.h.
10-12 Jul, from St. Croix to Camaguey; U = -13, C = -18 m.p.h.
15-16 Jul, Trinidad to San Juan; U = -16.5, C = -20 m.p.h.
30 Jul - 2 Aug, Trinidad to Port au Prince; U = -19.5, C = -24 m.p.h.

inches before and .07 inches after passage, the maximum taking place approximately six hours before passage. The distribution of the other weather factors was in general agreement with the rainfall. Considerably more weather occurred before passage than after. Overcast skies extended as much as 24 hours ahead, while rapid clearing took place on several occasions six to twelve hours after surface trough passage.

Comparison of the speed of the wave-trough with the mean flow between 5000 and 15000 feet normal to the trough indicated that, on the average, the waves moved 4 m.p.h. faster than the current in which they were embedded. The bad weather occurred farthest ahead of those troughs, where U-C was greatest and there was a general tendency for the intensity of the weather to decrease as U-C increased. This result compares favorably with the weather distribution indicated by Riehl (6) for waves that move more rapidly than their steering current, although in his analysis U strictly represents the zonal flow.

At a given station the period of showers and squally weather seldom exceeded twelve hours in connection with the passage of a fast wave. For aircraft operations the bad weather areas present less hazardous conditions than those associated with other types of waves. Usually there are only a few minutes of terminal instrument conditions and often no instrument conditions at all.

b) Moderate moving waves: Waves of moderate speed showed a uniform seasonal dispersion.[2] Since several of these waves deepened the periods of deepening were omitted for purposes of this study, beginning 48 hours before the deepening became apparent at the surface. Thus, waves in steady state conditions only were considered for 1944, and several steady state waves of the early part of the 1945 season were also added.

The average rainfall pattern shows the following: in the thirty hour period up to the time of surface passage, .19 inches of rain fell and in the thirty hour period after passage, .45 inches. Therefore, less than one third of the rainfall occurred before passage. Cloudiness before passage also was less intense in general than after passage. Thus the weather before passage is approximately normal but after passage becomes appreciably worse than normal. The disturbed weather lasted at least 12 hours and considerable cloudiness frequently persisted for an additional 12 hours.

The mean flow normal to the trough line from 5000 to 15000 feet was approximately equal to the speed of the waves. In one case it exceeded the wave speed by 3 m.p.h. and the worst weather was displaced farther to the rear in this compared to the other cases.

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[2] 8-9 Jul, British Guiana to Roseau; U = -14, C = -15 m.p.h.
9-11 Jul, Cayenne to Barbados; U = -19, C = -16 m.p.h.
13-16 Sep, Trinidad to Jamaica; U = -14, C = -15 m.p.h.
17-19 Sep, Trinidad to Puerto Rico;

Weather occurred in the form of frequent moderate showers, occasional heavy showers, and terminal instrument conditions persisted for intermittent periods up to 3/4 hour. Cumulonimbi and extensive altostratus and altocumulus decks accompanied the wave passages.

c) <u>Slowly moving waves:</u> There were three slowly moving waves during 1944.[3] All of these occurred late in the season, and two formed closed low centers. Prior to the deepening, .09 inches rain fell during a thirty hour period before passage and .32 inches or more than 75% of the total after passage. Compared to the normal rainfall during average weather for a ~~comparably~~ comparable thirty hour period (.15 inches), the rainfall before passage was considerably less than normal. The rainfall after passage compares to that associated with the moderate moving waves.

Maximum cloudiness, as well as rainfall, took place approximately 15 hours after surface passage. Duration of weather, type and amount of cloudiness, etc., resembled closely the sequence observed in connection with moderate moving waves. The primary difference between these two types of waves lies in the fact that the weather is considerably better ahead of the slow waves than the moderate moving waves.

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[3] 1-6 Sep, Trinidad to Haiti; U = -11, C = -8 m.p.h.
4-9 Oct, Trinidad to San Juan; U = -10; C = -7 m.p.h.
16-20 Oct, British Guiana to Haiti; U = -12, C = -8 m.p.h.

The relation between wind and trough speed gives a possible clue concerning this difference. The average flow normal to the trough line was 11 m.p.h. for the slow waves, while the wave speed was 8 m.p.h. Thus $U - C = -3$ m.p.h. in contrast to $U - C = 0$ for the moderate wave. This relation should, according to Riehl (6) produce divergence and fair weather before passage and convergence with squally weather after passage.

d) Deepening and decelerating waves: Deceleration of the speed of a wave during 1944[4] resulted in each case in the formation of a closed low of at least moderate intensity. Thus deepening and decelerating waves may be considered together as far as the 1944 waves are concerned. The tendency for deceleration increased as the season advanced, while the steady state waves occurred primarily early in the season.

The weather distribution around decelerating waves varied widely depending on conditions immediately preceding the deceleration. However, a typical sequence of changes can be found. The weather is generally distributed asymmetrically during the early stages of deceleration with the period of most disturbed weather approximately 12 to 15 hours behind the surface trough passage. As the deceleration progresses, the pattern slowly becomes mor symmetrical, and in the

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[4] 9-11 Jul, Cayenne to St. Lucia.
13-15 Aug, Dutch Guiana to Antigua.
13-16 Sep, Antigua to Jamaica.
17-19 Oct, St. Lucia to Puerto Rico

later stages the weather is worst approximately 6 hours after trough passage. Thus there is a gradual transition from the patterns association with steady state waves in the easterlies to those connected with tropical storms. During the transition, the intensity of the bad weather increases constantly. Therefore, as is entirely reasonable, deepening waves yield the most dangerous weather conditions.

It is noteworthy that, while the mean flow normal to the wave exceeded the wave speed during the early hours of the deepening, the speed of the wave and the mean flow became approximately equal as the deepening progressed. This changing relation, however, may no longer be used to interpret the shifting of the areas of convergence and divergence relative to the wave trough because of the non-steady state type of motion involved.

e) Accelerating waves: Only two instances of pronounced acceleration took place during 1944. In the two cases noted[5] the weather before acceleration was similar to that described in conjunction with slow moving waves. Initially, also $U - C < 0$. As the acceleration began, the weather distribution became more symmetrical, and $U - C \rightarrow 0$. Neither of the two cases could be followed to the stage where $U - C > 0$.

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[5] 30-31 Jul, Haiti to Cuba.
4-6 Sep, San Juan to Jamaica.

3. Conclusions

Fast

East moving waves (18 m.p.h.) are of weak intensity and have an approximately symmetrical distribution of weather about the wave trough.

Moderately moving waves (13-18 m.p.h.) are in general more intense than fast waves. The weather increases after the trough passage.

Slow waves (13 m.p.h.) are preceded by a pronounced zone of good weather and have maximum intensity of weather 12 hours after passage.

Decelerating waves, which develop into tropical storms, are the most intense of all types considered and gradually approach nearly symmetrical distribution of weather.

4. Appendix

In the study of weather conditions around a wave in the easterlies, use of rainfall data alone seems inadequate. It is obviously possible for rain gages to record unrepresentative amounts of precipitation in many instances. Therefore the other elements such as cloudiness and type of precipitation should be included. A formula embodying these factors was devised, namely:

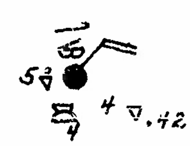
$$(C_L \times N_h) + (C_M \times N) + (ww \times RR) = \text{Weather Intensity.}$$

This empirical formula states that the low clouds considered with amount of low clouds plus middle clouds considered with total sky coverage, plus type of weather considered with amount of precipitation results in a picture of weather intensity. Since all clouds are not all equally important weather producing elements, the type and amounts were weighted according to the following schedule:

C_L		C_M		N		N_h	
C_L	Value	C_M	Value	Code Figure	Value	Code Figure	Value
1	= 1	1,2	= 1	1	= 1	1,2,3	= 1
2,4,5	= 2	3,4,5,6	= 2	2,3	= 2	4,5	= 2
6,7,8	= 3	7,8,9	= 3	4,5	= 3	6,7,8	= 3
3	= 4			6,7,8	= 4		
9	= 5						

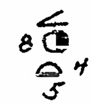
W or ww (but not both)	RR			
	Amount	Value	Amount	Value
Rain = 2	T	= 1	.50 - 1.0	= 4
Shower = 3	.01 - .10	= 2	1.0 +	= 5
Thunderstorm = 4	.10 - .50	= 3		

Thus each six-hourly synoptic observation can be assigned a weather value number, which may be referred to as the "weather integer". Two examples of a typical synoptic observation and their computed "integer" follow.



$$(C_L \times N_h) + (C_M \times N) + (ww)\,(RR)$$

$$(4) \quad (2) + (3) \quad (4) + (3 \quad .3) = 29$$



$$(C_L \times N_h) + (C_M \times N) + (ww \times RR)$$
$$(1) \quad (2) + (1) \quad (3) + \quad 0 \quad = 5$$

No attempt has been made to verify the value of the formula statistically. However the results, viewed qualitatively, offer a reasonably correct picture of the intensity of current weather. A graph of time versus weather integer provides a simple yet reasonably accurate picture of changing intensity at a particular observation point.

CHAPTER IV

MAINTENANCE

1. Basic Requirements

It has been shown in the chapter on Origin that the deep easterlies in themselves do not generate waves. Once a wave has formed, however, it is probable that deep easterlies are necessary to maintain it. Thus North Atlantic waves occur mainly in summer and early fall when the trades are most widespread.

There were several ways to verify statistically the above hypothesis. First the central pressure of the oceanic high was taken as a rough measure of the strength of the trades, with the assumption that any change should bring about a corresponding change in the pressure gradient to its south. The average central pressure, based on fifteen years data (1924-38) is 1029.3 mb in July, 1027.0 mb in August and 1025.9 mb in September. The average, however, for eight day periods prior to the appearance of a wave in the Caribbean, i.e. for the periods during which these waves were crossing the Atlantic, was:

1031.4 mb in July (six waves[1])
1028.2 mb. in August (22 waves) and
1026.0 mb in September (fifteen waves)

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[1] Only six out of the forty four historical waves occurred in July. From what was said above concerning the frequent occurrence of waves in July, it may appear surprising that such a small percentage of those selected from historical maps were July waves. The

Thus, in these situations, the central pressure of the high exceeded the monthly average by 2.1 mb in July, 1.2 mb in August, and 2.1 mb in September.

An even better test of the strength and depth of the easterlies may be obtained by measuring the zonal index of the trade wind area. For purposes of this study, this index was defined as the average pressure at 30°N. minus average pressure at 15°N., both taken in the zone bounded by the meridians 40°W. and 70°W. The average pressure along the parallels was determined by readings taken at the intersections of the parallels with the 40th, 50th, 60th, and 70th meridians. The area used to determine the index (Figure 7) was selected so as to coincide with the mean southern periphery of the subtropical high and thus yield the most representative figures for determining the strength of the easterly flow in the latitudes where waves are most common. For this reason it appears preferable to use the index as defined here rather than the subtropical index as employed by Namias. The index was computed daily for the nine months of July, August, and September 1936-1938 and for August, September, and October 1944, altogether twelve months. From the daily figures, monthly means were then computed. In addition, the mean value of the index was calculated for each four day period prior to the arrival of a wave in the Caribbean. The results are shown below.

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1 (cont.) answer lies in the fact that owing to the lack of upper air data only the more intense waves could be found on the historical maps, and July waves are seldom intense.

TABLE 3

	July 1936	July 1937	July 1938	Overall July Average
Monthly Average	7.9	6.8	8.5	7.7
4-day Average before each Wave	10.2 8.4 8.0 Ave. 8.9	7.3	10.1 9.3 10.3 Ave. 9.9	9.1

	Aug. 1936	Aug. 1937	Aug. 1938	Aug. 1944	Overall August Average
Monthly Average	7.7	8.1	7.4	5.6	7.2
4-day Average before each Wave	8.8 7.7 Ave. 8.4	10.6	9.1 8.4 7.5 8.1 Ave. 8.3	6.3 5.3 Ave. 5.8	8.1

	Sept. 1936	Sept. 1937	Sept. 1938	Sept. 1944	Overall September Average
Monthly Average	6.5	4.9	6.5	3.7	5.4
4-day Average before each Wave	6.8 8.5 8.4 Ave. 7.9	5.7 7.6 7.8 Ave. 7.0	7.1 6.2 8.6 Ave. 7.3	5.5 3.4 5.8 4.4 Ave. 4.8	6.6

	Oct. 1944
Monthly Average	3.3
4-day Average before each Wave	4.3 5.8 Ave. 5.0

The index for the four days preceding the arrival of a wave in the Caribbean exceeded the average monthly value in 28 out of 32 instances, and was the same in one case. It exceeded the overall monthly average in all instances, and by more than 30% in nine instances.

These figures show the usefulness of the index. Nevertheless, it is necessary to study the maps for any unusual feature that may detract from the value of the calculation. For example, the index may be unrepresentatively low if a hurricane is located near the calculation points on the 30th parallel, or unrepresentatively high if on the 15th parallel. Furthermore the index does not indicate what is occurring farther east in the Atlantic, where the data was too sparse for accurate computation. Thus a major wave or tropical storm may approach from the eastern Atlantic and then recurve north of the Caribbean into a big trough, in which case the index would be low.[2]

2. Additional Requirements

Cursory inspection of the historical maps seemed to indicate that, at the time of the formation of a wave near Africa, a pronounced high covered the subtropical eastern Atlantic, thus yielding strong easterlies to its south in which the newly formed wave began to move. This was further investigated by listing all the instances in the fifteen year period when for three or more consecutive days the high had broken down completely in the eastern Atlantic, either by a marked displacement to the west or by the intrusion of a polar depression into the Madeira Island area. There

[2] E. g., 8-14 Sep 1926, 22-25 Sep 1937.

were fourteen such periods and in each the following twelve maps were inspected on the theory that if a wave had formed near Africa, it would appear in the Caribbean approximately five to twelve days later. Only one wave appeared in these fourteen cases and this one was probably of mid-Atlantic origin.[3] This appears to be fairly conclusive evidence that waves do not move westward in the eastern Atlantic when there is no strong high in the area just to the west or northwest of the generating trough.

This conclusion next led to the supposition that if a pronounced high is essential in the eastern Atlantic when the wave forms, it should also be present in the central Atlantic when the wave is moving through this area, and in the western Atlantic when the wave arrives in the Caribbean. In other words, continued association of the wave with the strong easterly flow of the high is necessary for the maintenance of the wave. Thus the high either must extend across the entire Atlantic when the wave begins its movement westward, or the high must also travel westward matching the movement of the wave. Since single high cells extending over the entire Atlantic are a rarity, the second alternative should be most common.

This was largely borne out by the data. In thirteen cases of the 45 studied no appreciably motion was observed, and in one the high moved first to the northeast and then southwestward.[4] But in the case

[3]Case in which wave later occurred was 29 Aug-3 Sep 1929. Cases in which wave did not occur were 4-8 Aug 1925, 23-30 Sep 1926, 23 Sep-4 Oct 1928, and 28 Sep-2 Oct 1930.

[4] 15-24 Jul 1926.

of the remaining 31 waves, the high moved with a component toward the west in 25 instances,[5] (twelve west, ten southwest or west-southwest, and three northwest or westnorthwest). Only four moved with a component toward the east,[6] (one east, two southeast, and one northeast). The remaining two highs dissipated while a new high formed to their west and pushed southward.[7]

3. Conclusions

The following factors are favorable for maintenance and continued westward movement of waves in the easterlies:

a) Strong and deep easterlies, and a high value of the zonal index.

b) An oceanic high with pressure higher than normal.

c) An elongated high that covers the entire ocean or westward motion of the high cell situated to the north of a wave.

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[5] Examples are 11-17 Aug 1926, 9-21 Jul 1930, 29 Jul-10 Aug 1930, 16-23 Aug 1932, 29 Jul-5 Aug 1933, 19-25 Aug 1934, and 5-13 Sep 1936.

[6] Examples are 24 Aug-4 Sep 1930, and 6-12 Sep 1934.

[7] 15-20 Aug 1935 and 11-18 Sep 1938.

CHAPTER V

DISPLACEMENT

Three methods are commonly used in temperate latitudes for forecasting the movement of synoptic systems, namely, extrapolation, Petterssen's displacement formulae, and use of the wind component perpendicular to fronts. A study was made regarding the applicability of these three methods to the waves in the easterlies of the 1944 season.

1. Extrapolation

Because of scarce data, a forecaster must often extrapolate wave positions using an average rate of motion. This procedure should yield at least a fairly good first approximation. Therefore, it is of interest to determine that average rate. In the case of the 1944 waves, the fixes were reliable enough to give the overall movement to the nearest one or two m.p.h. The following table shows the average, maximum, and minimum rates of speed of the sixteen waves in the following areas: a) the entire Caribbean (Barbados to Havana), b) the eastern Caribbean (Barbados to Ciudad Trujillo), and c) the western Caribbean (Ciudad Trujillo to Havana).

TABLE 4

	Entire Caribbean	Eastern Half	Western Half
Average speed	15.7 mph (5¼ days)	16.9 mph	14.5 mph
Maximum speed	19.5 mph (4 days)	22.5 mph	22 mph
Minimum speed	11.5 mph (6.5 days)	8 mph	7.5 mph

It was more difficult to obtain accurate fixes and rates of motion east of the Caribbean. However, from Georgetown, B.G., to Trinidad an average of 16.9 mph was found, the same as in the eastern Caribbean.

Waves of the earlier part of the season traveled fastest with an average of 17.5 m.p.h. for July and 17.6 m.p.h. for August, while September waves had a speed of only 12.1 m.p.h. and October waves 13.0 m.p.h. This is in accordance with what has been stated in the previous chapter concerning the seasonal variation in the strength of the trades.

Even more important than the average rate of motion is the change of speed with time, since the amount of change shows how reliable extrapolation forecasts can be. The following large changes were noticed:

TABLE 5

Acceleration

10.5 to 13.5 m.p.h.	These were the only examples noted when the speed increased by more than 10%.

Deceleration

20 to 13 m.p.h. 16 to 11 m.p.h. 19.5 to 13.5 m.p.h. 12 to 8.5 m.p.h. 22 to 17.5 m.p.h.	The maximum deceleratio noted was 65% of the original speed.

Even in these cases, the change is not large from the viewpoint of 24-hour forecasts, mostly because the values themselves are small. Extrapolation from past positions using a constant rate of speed thus should be fairly accurate.

Deceleration will be discussed in relation to deepening, but there is a simple relation between deceleration and the speed of the easterly current, evidenced in each of the five 1944 cases listed above. When the easterlies slacken, the waves also slow down. The slackening occurs mainly when a low center or strong extratropical trough moves to the north of the wave. Thus a wave that moves into a region of decreasing easterlies will tend to decelerate. The converse also holds, and a wave that moves into a region of increasing easterlies, will tend to accelerate. This is borne out even by the mean flow: waves that move from the eastern into the western Caribbean lose speed, as shown in Table 5, and this deceleration is due to the fact that in the western Caribbean the wind loses its westward component and veers to a southerly direction as it rounds the western edge of the subtropical high.

In conclusion it may be stated that:

a) Extrapolation at constant speed will yield good forecasting results, if the pressure gradient north of a wave remains constant.

b) Deceleration should be forecast if a wave moves toward an area of lighter winds normal to its troughline.

c) Acceleration should be forecast if a wave moves toward an area of higher winds normal to its troughline.

2. Wind Component Perpendicular to Wave.

The motion of a wave relative to the earth can be divided into a dynamic component and a translatory component. The latter represents the speed of the current in which the wave is travelling. In order to see to what extent the total speed of the waves approximates this translatory component, the components of the wind perpendicular to the wave at various levels were computed for fourteen 1944 waves. The average magnitude of this component was obtained from all the stations in the immediate vicinity of the wave. In each case the measurements were made when the wave was located in the eastern or central Caribbean. Eight waves moved at a rate of eighteen mph or more, and the remaining six moved at no more than 14.5 mph. The average wave speed and wind speed across the wave for the eight fast-moving and the six slow-moving waves follow:

TABLE 6

	Average Actual Wave Speed	Mean Wind at 5000 ft.	Mean Wind at 8000 ft.	Mean Wind at 10000 ft.	Mean Wind at 12000 ft.
Fast-Moving Waves	19.1 mph	21.6 mph	19.6 mph	19.4 mph	16.6 mph
Slow-Moving Waves	11.3 mph	14.0 mph	11.7 mph	11.0 mph	10.6 mph

The speed of both slow and fast moving waves approximated the translatory component very closely at 8000 and 10000 feet. It must be remembered, however, that these are only mean figures, and in some individual cases, the wind at all levels differed from the wave speed. There were four notable examples of this during 1944. Twice the development of a low center rendered winds along the Antilles chain unrepresentative, and twice a wave moved considerably in excess of the wind at all levels for reasons which are not obvious.

On the whole, however, the correlation between wave speed and translatory component is certainly pronounced enough to be of practical use. The flow perpendicular to the wave serves as a good indication whether the wave will move faster or slower than the average. As a first approximation, one might conclude that the wind at 8000 and 10000 feet should be the most useful forecasting tool. The problem, however, was further tested in each of the fourteen cases. It appeared that the wind at less than 5000 feet was most representative in four cases, at 5-8000 feet in two cases, at 8-10000 feet in two cases, above 10000 feet in two cases, and above 12000 feet in two cases. In two cases any level would have served almost equally well.

Since it was felt that a few specific waves of one season might not form a large enough sample to find truly representative conditions, resultant east wind components from San Juan, P. R., and Cayenne, F. G., rawins were obtained for each month of the summer of 1944. Also the resultants for each period prior to and following passage of a wave at these two stations ~~was~~ were calculated from the two ascents immediately before, and the two ascents immediately after passage of the wave trough. Resultant east wind components were also computed from Stone's compilation of upper winds at San Juan obtained from eighteen years of pilot balloon observations. Since the average speed of all 1944 waves was about 15.5 mph, it was next determined at what level the mean east wind component was nearest that speed. The results for San Juan are listed below.[1]

TABLE 7

	Best June Level	Best July Level	Best August Level	Best September Level	Best October Level
Monthly Resultant Rawins	less than 10000'	10000'	15000'	less than 10000'	less than 10000'
Stone's Monthly Resultant Winds	9000'	12000'	7-8000'	5-6000'	4000'
Resultant Rawins during Wave Passage	———	just over 5000'	10000' to 15000'	less than 5000'	inconclusive; probably 5000'

[1] The Cayenne figures computed were far less valuable, with little variation of the wind with height all the way up to 30000 feet. The only definite conclusion to be drawn would be that the steering current is not over 35000 feet, hardly a surprising result.

The only definite conclusion to be drawn is that the level which approximates the average wave speed closest lies somewhere between 4000 and 15000 feet. If the extremes of October and July-August can be reconciled at all, the range narrows to 5000-12000 feet. It is possible that the most representative level is higher in July and August, when the trades are strongest, and lower in June, October and late September. The conclusions to be drawn are:

a) The levels whose average wind component normal to moving waves agrees most nearly with the wave speed are 8000 to 10000 feet. For practical use in individual situations, however, it is recommended to make use of the mean wind vector between 5000 and 12000 feet normal to the wave troughs.

b) The wind normal to a wave is a less reliable forecasting tool when applied alone than is extrapolation; consequently it should only be used when no accurate past positions are known. The method, however, does appear to have some value in conjunction with extrapolation, and its use is recommended for qualitative purposes, i.e. to determine at least whether a wave will move faster or slower than the average.

3. Petterssen's Formula for Trough Displacement

$$c = L \; \frac{b(\frac{1}{2}L) - b(-\frac{1}{2}L)}{p(L) - 2p(0) + p(-L)}$$

Where "L" is the unit of length chosen,

"t" is the pressure tendency,

"p" is the pressure.

This formula is difficult to apply in the tropics because of the large effect of the diurnal pressure variation on the three-hourly tendencies. The latter must be corrected before a computation is possible. To test the formula, the movement of the 1944 waves was calculated using a) 24-hour tendencies and b) three-hourly tendencies corrected for the diurnal change for the month in question. The eastern Caribbean was the area tested because farther east there are no reporting stations north of 7°N. lat. and farther west waves are generally weak. Sample results of the application of the formula in twelve cases are shown below:

TABLE 8

Date	Location of Wave	Computed Speed from Corrected Three-hourly Tendencies in mph	Computed Speed from 24-hour Tendencies in mph	Actual Speed in mph
10 Jul	St. Croix	26.5	12	19
10 Jul	Mona Passage	11.5	12	19
11 Jul	St. Lucia	15	7	19.5
12 Jul	St. Kitts	22	6	19.5
12 Jul	Puerto Rico	38	9	16
13 Jul	Ciudad Trujillo	12.5	1	13
16 Jul	Antigua	52	5	21
24 Jul	St. Lucia	10.5	25.5	18.5
28 Jul	Puerto Rico	0	27	13
1 Aug	Antigua	15	0	~~22.5~~
15 Aug	Puerto Rico	26.5	3.5	22
18 Aug	Puerto Rico	18.5	30	19.5

The results of the computations using the 24-hour tendency are poor. In no case was the computed speed within even six mph of the true speed. One difficulty lies in the fact that most waves do not appear as very pronounced troughs in the pressure field. Another obstacle is encountered in the selection of the interval "L" when using 24-hour tendencies. "L" must be fairly large to eliminate the likelihood of analysis errors. Further, if b $(-\frac{1}{2}L)$ is to represent the true tendency behind the trough and the slope of the tendency profile, $-\frac{1}{2}L$ must be located far enough behind the trough line so that the pressure is rising during the entire 24-hour period. This means that "L" must be at least as large a distance as the trough has moved in two days. At such a distance ahead of or behind the trough, the next wave trough may be approached, so that the denominator in the formula does not really represent the curvature of the pressure profile on the two sides of the trough.

The results using corrected three-hourly tendencies are somewhat better but nevertheless also very disappointing. In five of the twelve cases the difference between computed speed and true speed was even greater than that obtained from 24-hour tendencies, and in only three cases did the computed speed differ from the actual speed by four mph or less.

Why do not the corrected three-hourly tendencies give better results than the 24-hour tendencies? First, the diurnal pressure change has not been computed as yet with sufficient accuracy at most Caribbean stations. For example, it is questionable whether the diurnal maxima and minima fall at exactly the same hour every day in the month. Second and more important, it is doubtful whether a system of no steeper pressure profile than a wave in the easterlies will yield a significant pressure change at any station in as short a space of time as three hours. For example, a 3.5 mb total fall ahead of a wave would be considered indicative of a strong wave. If this fall is distributed over a two-day period, the mean fall every three hours of the period would be only about 0.2 mb. Barometers are not read accurately enough to measure 0.2 mb pressure changes with great accuracy; thus a mistake of 0.1 mb in reading would change the computed speed by 50%.

These results do not necessarily mean that the formula has no application in the tropics. However, it does seem fairly certain that, whatever the cause of the failure, it is definitely not recommended at this time for use in forecasting the movement of waves in the easterlies.

CHAPTER VI

INTENSIFICATION

The problem of intensification of waves in the easterlies is important for the forecasting of the formation and deepening of tropical storms in the western Atlantic, since many hurricanes developing there are derived from such waves. Formation of a closed low on a wave is the most conclusive evidence of intensification and for this reason the circumstances attending the development of closed circulations will be discussed.

1. Extratropical Troughs

The synoptic situations that are favorable for the formation of a wave when there was none before, may also be favorable for intensification. Since polar troughs have been considered in this report as the main generating agent, polar trough situations were investigated for deepening. To be an effective agent of intensification, a trough must be deep enough to extend into and influence the tropical regions but not so deep as to destroy the deep easterlies necessary for maintenance of the wave. This statement is entirely in agreement with that given recently by Riehl and Shafer (7).

Evidence in this discussion has been derived from a study of 1) cases of formation of lows and 2) cases of deepening of existing lows.

a) Formation of lows (Eastern Caribbean): In many instances when a low appeared on waves in the Lesser Antilles it was impossible to tell from the Atlantic data how much farther east the low actually formed and under what synoptic conditions. But there were seven excellent examples of waves on the 1924-38 historical maps that initially contained no closed circulation but which later developed a center as they passed under polar trough in the eastern Caribbean.[1] A similar development took place in early part of October of 1944 when a wave moved into a stationary extratropical trough over the Lesser Antilles and decelerated. A closed low formed on that wave and moved northward. More will be said on the formation of lows in this area under the heading Deceleration in a later portion of this chapter.

b) Formation of lows (Western Caribbean): There were many excellent instances when a low formed in the western Caribbean or Gulf of Mexico on a wave as it moved under a polar trough.[2] While many hurricanes in those areas form on other types of systems, the evidence is convincing that at least a good percentage develops on the waves. All hurricanes and storms from 1924-1938 were studied whose paths were shown by Tannehill (10) as beginning in the western

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[1] Examples are 7-9 Aug 1928, 10-13 Sep 1931, 25-28 Sep 1932, 7-12 Sep 1933, and 22-24 Sep 1935.

[2] Representative cases are 20-25 Aug 1926, 17-21 Jul 1933, and 28 Sep-3 Oct 1937.

Caribbean, west of 70°W, or in the Gulf of Mexico. There were fifty ~~fifty~~-two such storms. Of these, 22 definitely formed on waves which entered the area from the east, and fourteen other storms also may have formed on waves.[3] In addition, a number of disturbances shown by Tannehill as developing farther east, that unquestionably were derived from waves in the easterlies, first developed closed circulation in this area.[4] This evidence indicates that waves in the easterlies are not to be over looked in forecasting the formation of hurricanes in the western Caribbean.

Formation of closed circulations on waves in this area may occur in several types of situations. A triple point formed by the intersection of the equatorial front with a wave may become active. Similarly it is feasible that both a wave and a polar trough are complementary in reinforcing each other in the formation of triple point storms. This possibility was tested further by determining 1) whether a wave was under the influence of a mid-latitude trough at the time of closed low formation and 2) whether the low appeared

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[3] Although most storms that develop in the western Caribbean occur early in the season (June) and again late in the season (Oct. and Nov.), those forming from waves tended to occur in mid-season. Thus of the seven June storms on the list, none originated on waves and of the five November storms none were definitely marked as such although three were of doubtful origin. This should be expected because of the known infrequency of waves in June and November.

[4] See 12-19 Aug 1933.

to have formed on the equatorial front. The latter factor was decided mainly on the basis of area of formation, since the exact location of the front was often difficult to determine. The results from the 36 examples are given in Table 9.

TABLE 9

	Extratropical Trough Present	No Extratropical Trough	Doubtful
Formation on Equatorial Front	7	2	1
Formation not on Equatorial Front	8	0	0
Equatorial Front formation doubtful	10	5	3

Eliminating the doubtful figures, several major features stand out. In all cases either a polar trough or the equatorial front played a part. Cooperation of one or the other appears to be necessary for intensification. Action of the equatorial front alone rarely will cause the formation of a storm on a wave (2 cases). The coincidence of both a polar trough and the equatorial front in the western Caribbean at the time a wave in the easterlies arrives there is favorable for formation (7 cases). However, a wave and a polar trough can also get along well without the aid of the equatorial front, since eight of the 17 centers not in the doubtful column developed under such circumstances.

c) Deepening of Lows: A similar test was made concerning the deepening of tropical storms that already had developed from waves in the easterlies. Whenever the central pressure was available with fair accuracy on several successive map periods, it was noted whether it deepened and whether a polar trough passed over it. Cases in which the low merely recurved northward into a trough without deepening were excluded. The results obtained were as follows:

TABLE 10

	Waves Deepening	Waves not Deepening
Polar Trough Moved over Wave	7	2
No Trough	2	12

Thus the results verify the hypothesis in nineteen out of twenty three cases. Only four instances remain in doubt, two where deepening occurred and two where it did not occur.[5] Thus a wave or tropical storm that moves under a trough will usually intensify, and if it does not move under a trough it will seldom intensify. These statistics apply to pre-existing closed lows, but similar conclusions should also apply to the formation of lows from waves and the deepening of waves not containing closed lows.

[5] Cases of lows deepening in troughs include 16-18 Sep 1928, 4-9 Sep 1932 and 27-31 Jul 1936. No deepening and no trough in evidence 5-8 Aug 1928, 8-12 Aug 1928, 23 Aug 1930, 13 Sep 1931, 11 Aug 1932, 27 Jul 1933, 2 Sep 1933, 27 Sep 1933, 23 Jul 1934, 11-14 Aug 1938, and 23-26 Aug 1938. Examples of exceptions to the rule are 16-20 Aug 1933 (trough but no deepening) and 20-23 Aug 1927 (deepening but no trough).

2. Deceleration of Waves

Both in tropical and extratropical regions, lows that decelerate frequently strengthen, and fast-moving systems rarely intensify. Indeed tropical disturbances seem to conform more closely to this rule than temperate latitude systems. The theory behind the rule has never received adequate explanation. In particular, it is not clear whether the deceleration causes the intensification or vice versa. Merely the coincidence of both is known and the combination occurs with sufficient reliability in the tropics to be of definite use. If deceleration occurs, one should forecast deepening and vice versa. The question of cause and effect, and also of the chronological sequence involved, is difficult to answer.

The converse rule, that fast-moving or accelerating waves should fill or weaken, is of less certain validity. Dunn (3) suggests that the reason for such filling may be that a fast-moving wave outruns the rolling back of the dry inversion. However, if the rise of the inversion is merely the result of convection caused by the wave or storm itself, it is difficult to see why the rise of the dry inversion should not always move at the same speed as the wave itself, however rapid that speed may be.

Deceleration has been treated here as one independent cause or effect of strengthening while polar troughs have been listed as another. But deceleration unquestionably is also related to the action of troughs. The latter reduce the strength and depth of the easterlies and substitute a predominately meridional rather than latitudinal flow. Hence they tend to cause a deceleration of westward moving systems. For example, hurricanes decelerate just before recurving, and the recurving almost invariably is directed into a polar trough.

The following examples taken from the 1944 waves bring out the relationship between decelerating and deepening discussed above.

In mid-July, three waves passed the Lesser Antilles in one six day period. The first and third moved at rates of 19 and 21 mph, respectively, across the Caribbean, a high speed even for July. Neither formed a tropical storm. But the second had an average overall speed of only 15 mph. It moved as far as Borinquen Field, P. R. at 19.5 mph, approximately as fast as the other two, but then it slowed down to only 12.5 mph. A small tropical low on the wave intensified between Hispaniola and the Bahamas and moved northward between Bermuda and Cape Hatteras as a rather intense tropical storm.

In late July, a storm appeared on a wave near Barbados. Storm warnings were sent out because it appeared fairly intense. However, the wave moved at the unusual speed of 19.5 mph and accelerated from 18.5 to over 19.5 mph. Thus the low would be expected to fill, which it did. When the wave was within 100 miles of Jamaica, a closed circulation no longer could be located.

In mid-August two intense waves crossed the Caribbean less than three days apart. The first one moved very rapidly, with a speed of 22 mph as far as Ciudad Trujillo and with an average speed of 19.5 mph through the whole Caribbean. A low reported in the Lesser Antilles never developed but slowly dissipated despite the intensity of the wave. The second wave moved more slowly, averaging 17 mph as far as Puerto Rico and then slowing to 13.5 mph beyond Port-au-Prince, yielding an average overall speed of 15 mph, less than average and considerably less than the mid-season average. The closed low which appeared on this wave in the Antilles developed at first slowly. After the storm decelerated, however, it intensified and hit Grand Cayman with winds of hurricane intensity.

3. Location of Forming Center

Once intensification is forecast, the problem remains to say in what portion of the wave the closed low center will appear. Climatologically, the mean position of low centers that pass through the Lesser Antilles advances northward during the early part of the season and recedes southward again toward the end (c.f. 10) These mean paths, however, include storms that formed far to the east of the Lesser Antilles and the positions of centers developing near the island chain do not necessarily follow this seasonal pattern.

There is a better indicator than pure climatology to estimate the position where the closed low will appear. Although sufficient examples were lacking to obtain reliable results statistically, the lows seemed to appear at the latitude of greatest cyclonic shear, i.e. at the point where the north south pressure profile shows the greatest curvature. (Fig. 8). South of this point the easterlies will be weak and to its north strong. In addition, the cyclonic curvature of the isobars also is greater there than at any other portion of the wave. Thus, if isobars can be drawn with reasonable accuracy, their spacing will furnish a clue regarding the spot where the low center will appear.

4. Conclusions

a) Deceleration of waves is accompanied, in concurrence with Petterssen's rules, by the intensification while acceleration is usually, but not necessarily, accompanied by dissipation.

b) Synoptic features, such as polar troughs, that tend to decelerate waves, produce intensification provided they are not so deep as to destroy the easterly circulation of the tropics.

CHAPTER VII

TERMINATION

The problem of forecasting termination of a wave may be visualized as simply the converse of that of forecasting maintenance. The wave dies out when the conditions needed for continuance, mainly the strong deep easterlies, cease to exist. What then may cause the deep easterlies to disappear and prevent a wave from being maintained in its westward course?

1. Nature of Termination

a) Transformation: One suggestion that appears immediately is that the lowering of the base of the westerlies at the approach of a strong polar trough causes the termination. This may seem a paradox. As shown in the preceding chapter, a meeting of a wave with an extratropical trough tends to cause an intensification of the wave and now it is also suggested that such a meeting brings about the process of termination. Intensification and termination, however, are not inconsistent or opposite processes. For the type of termination considered now is merely one of loss of identity. The wave becomes part of the extratropical trough, and neither its area of bad weather nor its cyclonic circulation need to weaken. On the contrary, such a juncture usually tends to reinforce the bad weather area. In the cases discussed in the last chapter, however, the base of the westerlies remained sufficiently high to permit the tropical wave to retain its identity and properties, while in the present instances the base of the westerlies lowered sufficiently to alter the nature of the wave. The lowering will be especially marked if a pronounced front follows the trough into the tropics. Such a system may be considered as an insuperable obstacle for a wave in the easterlies. Numerous examples were found in which termination occurred in the manner just described.

In certain cases when the polar trough is unusually intense, another factor appears which may cause not merely the loss of identity of the wave but a dissipation of the cyclonic circulation and the bad weather accompanying it especially if the wave contains a closed low center. The circulation around the trough will cause the recurvature of such a closed center out of the wave. There is generally an area of subsidence south of the low, i.e. in the east-west ridge which separates the tropical low from the equatorial low. Thus the wave trough becomes disconnected from its low to the north by this zone of good weather and weakens.

Generally it is true that a polar trough deep and intense enough to cause recurvature of the closed low center will also block the westward motion of the parent wave and envelop it, at least its northern portion. At times, however, the southern extremity of the wave may continue to move westward as an independent entity. Several conclusive cases were found where the polar trough was sufficiently weak or moved eastward fast enough so that the southern part of the wave did not die after its storm recurved.[1] This took place mainly when the storm recurved northward rather sharply and rapidly at an early stage, mostly to the northeast or east of the Lesser Antilles. The southern part which continued on its westward course, was weak under such circumstances, and there were only rare cases[2] when it continued as a very pronounced wave or later reintensified.

The question arises where one may expect to find deep troughs such as might transform a wave. In summer the Bermuda high is strong and consequently few troughs north of the eastern or central Caribbean or central Atlantic penetrate into the tropics. In the Gulf of Mexico and western Caribbean, however, the mean flow is more southerly than easterly, and seldom more than a weak arm of the oceanic high lies north of this area. Thus temperate latitude troughs frequently penetrate into this region even in summer and cause the stagnation of waves in the easterlies. The data verified this contention very clearly. A record was kept as to where and how often each of the 26 most marked waves taken from the historical maps moved under a polar trough. (Table 11). The waves encountered 30 troughs; eight meetings took place in central Cuba,[3] six in western Cuba[4], and four in the Yucatan Channel.[5] Thus eighteen meetings occurred between

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[1]For example, 1-9 Aug 1926, 22 Sep-3 Oct 1937.

[2]22 Sep-3 Oct 1937. Sep 21-24, 1924.

[3]For example, 12-17 Aug 1924, 7-12 Aug 1930, 3-12 Jul 1931, 25 Sep-2 Oct 1932, 24-31 Aug 1937, and 24 Sep-3 Oct 1937.

[4]For example, 18-25 Aug 1926, 19-25 Aug 1929, 2-9 Sep 1931, and 13-21 Jul 1933.

[5]For example, 13-18 Sep 1925. 5-9 Aug 1926, and 22-27 Jul 1936.

80°W and 87°W Long. Two more took place in eastern Cuba[6] and two in the Windward Passage.[7] This result offers good evidence that northern troughs frequently are the cause of termination. As an indication of the frequency of trough occurrence, it may be noted that of the 26 waves, all but two of them moved into at least one trough, and in six cases waves encountered two troughs.

b) <u>Dissipation</u>: An active polar trough is by no means the only cause for termination of waves in the easterlies. In many instances the waves lose their identity in the broad area of southerly winds, divergent isobars, and flat east-west pressure gradient west of the Atlantic high. (Figure 9). In these situations full dissipation takes place, not merely a transformation into a different type of synoptic system. The cyclonic circulation gradually dampens and the attendant bad weather area disappears or drifts into the westerly belt as suggested by Riehl (8).

The dissipation most frequently occurs east of the Mississippi basin. Only if an arm of the Bermuda high extends far westward over the Gulf coast, or a separate high cell exists in that area, will a wave travel westward all the way across the Gulf of Mexico. (Figure 10).

How far west do most waves go before terminating? To obtain a quantitative estimate, the sixteen waves of 1944, to which six

[6] 6-12 Sep 1931 and 26-30 Aug 1932.

[7] 12-16 Aug 1930 and 10-15 Sep 1934.

more were added for this study, were followed as far west as they were traceable. This was also done for all the waves from the historical maps which had not developed closed circulation before reaching longitude 75°W. There were 26 such waves. The figures below indicate how far west these waves were last seen.

TABLE 11

	Historical Series	1944 Waves
Mona Passage	0	1
Ciudad Trujillo	0	6
Port-au-Prince	0	2
Windward Passage	1	1
Eastern Cuba	1	1
Central Cuba	1	0
Western Cuba	3	4
Yucatan Channel	3	0
Yucatan Peninsula	3	0
Mobile, Ala.	1	3
New Orleans, La.	4	1
Lake Charles, La.	2	0
Brownsville, Texas	7	3

A seasonal breakdown of the above figures showed, as expected, that waves in mid-season go farthest west. In contrast, none of the four October and two June waves of 1944 went beyond the Windward Passage.[g]

The preceding discussion is not applicable to the very southern extremities of the waves. Of the sixteen principal waves of the season, twelve could be followed past Curacao. There was seldom weather

[g]Waves going west all the way to the Texas coast on the following dates: 9-18 Sep 1925, 2-12 Jul 1931, 18-30 Aug 1936, 13-22 Aug 1944, 17-27 Sep 1944. Examples of waves terminating very far east include the following, all of which were last found near Ciudad Trujillo: 22-26 Jun 1944, 15-17 Jul 1944, 31 Jul-2 Aug 1944, 26-29 Aug 1944, 13-15 Oct 1944, and 16-20 Oct 1944.

with wave passage, but the windshift and tendency change could normally be found. Farther west, however, the situation was more doubtful. A careful examination of the surface and upper-air data from Barranquilla, Colombia, showed that only three of the sixteen waves definitely passed this station, and even these three appeared to be very weak. Measuring intensity by 72-hour precipitation (36 hours before and after passage), one of them caused no rain whatever,[9] one gave only a trace[10] and the third gave only .21 inches of rain.[11] In view of this result from the Barranquilla data, it is safe to assume that still farther to the southwest, waves are at least as uncommon. As expected, there was no conclusive evidence of any of the waves in the Panama Canal Zone.

What is the explanation for the weakness and scarcity of waves in Colombia and Panama? Just to the east of Barranquilla lie highlands and mountains and one summit attains an altitude of approximately 19,000 feet. West of Barranquilla the coast is oriented nearly northeast-southwest. These topographic features seem to cause a blocking of the easterly flow and produce what appears to be a cyclonic eddy west of the mountains. Thus the following factors may be the explanation of why so few waves reach Barranquilla and Panama.

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[9] 10-11 Jul 1944.

[10] 15-16 Aug 1944. This was one of the strongest waves of the entire season in the Antilles region.

[11] 19-20 Sep 1944.

The wave may dissipate in the highlands to the east.

The eddy may break up the easterlies needed to maintain the wave.

The orientation of the coastline is unfavorable for maintenance.

2. Criteria for Forecasting Termination

a) Zonal Index: Since the termination or dissipation is in one sense the converse of maintenance, the first criterion which suggested itself as a forecasting aid was the zonal index. For the present problem, the index was computed for the area bounded by the 65th and 95th meridians west and, as before, by the 15th and 30th parallels. (Figure 11). Mean values of the index were calculated for August and September 1931, July 1933, and July, August, September and October 1944, seven months in all. In addition, the average index for the three-day period when each wave was nearest the central Caribbean (70°W-75°W) was calculated. The results appear below:

TABLE 12

	Jul 1933	Jul 1944	Overall July Average
Average for Month	5.2	3.7	4.45
Three-day Average for each Wave Dissipating Far West (New Orleans or Beyond)	6.1, 5.3 } Ave. 5.7	4.2	5.2
Three-day Average for each Wave Dissipating Early (East of Windward Passage)	111	1.5, 0.7 } Ave. 1.1	1.1

	Aug 1931	Aug 1944	Overall August Average
Average for Month	6.6	4.7	5.65
Three-day Average for each Wave Dissipating Far West (New Orleans or Beyond)	8.8	6.2 7.7 Ave. 6.95	7.6
Three-day Average for each Wave Dissipating Early (East of Windward Passage)	4.5	3.0 4.1 4.9 Ave. 4.0	4.1

	Sep 1931	Sep 1944	Overall September Average
Average for Month	6.1	4.0	5.05
Three-day Average for each Wave Dissipating Far West (New Orleans or Beyond)	7.1 4.6 8.4 Ave. 6.7	3.8 5.7 5.3 Ave. 4.9	5.8
Three-day Average for each Wave Dissipating Early (East of Windward Passage)	—	—	—

	Oct 1944
Average for Month	6.4
Three-day Average for each Wave Dissipating Early (East of Windward Passage)	1.1 4.9 5.2 Ave. 3.7

Of the twelve waves that moved far west, ten occurred when the index was higher than the monthly mean. In every month the average for all such waves was higher than the monthly mean. Similarly, the index was lower than the monthly mean in eight cases out of nine, when termination took place very early. Again, in every month the average for all early terminating waves was lower than the monthly mean.

This is indeed good correlation. Nevertheless, the index approach, though useful, is not quite as helpful for forecasting termination as it is for forecasting maintenance. Using the index as a tool, the forecaster assumes that conditions in the future will remain much as they are when calculation is made. If trends are long and slow, this assumption is justified. For example, a strong mid-Atlantic high requires considerable time to be broken down by eastward-moving troughs. Thus the index in the eastern Caribbean and Atlantic as a rule changes slowly. Over the western Caribbean and Gulf of Mexico, however, large highs seldom persist and thus the index may change rapidly from one day to the next.

b) Westward extension of the Bermuda High: Aside from the zonal index, there are other ways to measure the strength of the easterlies, that are useful for forecasting wave dissipation. One such measure, the westward extension of the Bermuda high, was applied to the historical maps. If an arm of the high extends far west, deep easterlies should prevail over the Gulf. The extension of the high was measured by noting the point where the 1016 mb. isobar of the high crosses the United States Gulf coast. The farther west this occurs, the stronger should be the easterlies.

On the average the 1016 isobar crosses the coast near Lake Charles, La. In ten out of the fifteen cases when a wave travelled as far west as Pensacola, Fla., the 1016 isobar crossed the coast at Galveston, Texas, or beyond, at the time the wave was over central Cuba. In only two out of twelve cases when a wave dissipated east of Pensacola, did the 1016 isobar cross the coast as far west as Galveston. Thus there is a definite correlation between the point of termination of a wave and the extension of the Bermuda high. Frequent complication of the pattern due to the presence of migratory highs north of the Gulf coast accounts for the fact that the correlation was not entirely satisfactory. Such highs at times produced strong easterlies along the Gulf coast, even though the Bermuda high was located entirely over the ocean.

c) Speed of waves: It might be expected that fast-moving waves would go far west since: 1) their speed should indicate the presence of strong easterlies, and 2) deceleration, stagnation, and transformation are necessarily slow processes. From another standpoint the reverse might be expected since it is observed that decelerating and slow-moving waves frequently intensify, fast-moving or accelerating waves might dissipate. A test was made using the waves on the historical maps, but no correlation, either negative or positive, could be found between the time and place of termination and the speed of the waves. The average speed of those waves that went all the way to Texas and those that stagnated or disappeared in eastern Cuba or Hispaniola proved to be very nearly identical.

d) Other criteria: Another criterion of dissipation that suggests itself is a comparison of 24-hour pressure tendencies ahead of and behind the wave. However, two difficulties are immediately apparent, apart from what has already been said in the chapter on Displacement concerning the use of pressure tendencies.

1) The 24-hour tendencies are a tool of analysis rather than of forecasting. They show how the system has moved rather than how it will move. Three-hourly tendencies, if accurate and freed from diurnal considerations, should be most indicative of conditions at the end of the period involved.

2) Tendencies and tendency contrasts ahead of and behind the system are functions of two factors, the intensity of the system and its rate of movement. It is impossible to isolate these two factors by the use of pressure tendencies alone. Comparison of the tendencies ahead and behind a wave at several successive periods should yield better results.

Still another clue valuable in dissipation forecasting is the intensity of the extratropical lows and fronts that pass to the north. What was said under Origin and Intensification concerning the troughs associated with such lows should be applicable also in dissipation forecasting. Thus, a deep, slow-moving polar low located south of its normal summer track tends to break down the tropical easterlies and envelope the tropical waves. On the other hand, a weak rapidly-moving frontal low located far north, with a fairly shallow associated trough and little meridional wind component is not likely to transform a wave to its south or break down the subtropical high.

Correct judgment of the type of trough involved is a synoptic matter, and not a problem that lends itself well to statistical treatment. A qualitative examination of the instances, however, when waves went far west across the Gulf bears out the hypothesis. At least one polar trough passed to the north of most of these waves in the Gulf or western Caribbean, and penetrated into the tropics at least to a limited extent. But the troughs were rather weak, and their parent lows far to the north, shallow, and fast-moving. Thus they did not absorb the waves.

3. Effect of Waves in the Easterlies on Temperate Latitude Weather

In following waves across the Gulf of Mexico, it was observed that the cyclonic curvature of the isobars and the windshift from northeast or east to southeast, sometimes extended into central Georgia, Mississippi, Alabama, and Louisiana. Riehl (8) has noted such occurrences even farther north. Irrespective of how pronounced is the influence of waves on the weather in their northerly portions, they nevertheless do exist and have a marked effect on the winds. It is doubted whether most temperate latitude forecasters fully appreciate this fact. In at least one case the analyst of the Northern Hemisphere maps drew the windshift due to a wave in the easterlies as a north-south oriented cold front, south of a westward moving polar front wave; then after observing its retrogression westward for two maps, he dropped it altogether.[12]

Forecasters have often mentioned the possibility that waves, on entering the southerly circulation normally present in the Gulf in summer, swing around the west side of the high, steered by the windflow and appear on the United States Gulf coast oriented east-west with a windshift from southeast to southwest with passage. A search was made in the historical maps for evidence of such waves, but not one could be found. The explanation for this failure is given by Riehl (8) who showed that the waves may enter with pronounced windshifts in the middle troposphere, but, due to low level compensation, the surface isobaric field will show hardly any reaction. From the historical maps, these upper windshifts, therefore, could not be inferred.

The influence of waves on the temperate latitudes is not always restricted to the mere northward extension of the waves themselves. Convincing evidence was found that the presence of waves may have a profound influence on the behavior of frontal systems over the continent. Three cold fronts were noted which had moved into the Gulf or the Bahamas and then stagnated with an orientation more or less east-west. As soon as a wave passed to the south[13],

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[12] 29 Aug-3 Sep 1932.

[13] 7-10 Aug 1926, 13-16 Aug 1930, 6-12 Sep 1944.

they returned northward as warm fronts driven by the southeast winds to the rear of the wave. On two other occasions polar front waves formed on stationary fronts in the Gulf or in southeastern United States directly to the north of the apex of a wave in the easterlies.[14]

In these instances the northerly component to the west of the tropical wave and the southerly component to its east apparently extended far enough northward to set up a similar circulation across the front, hence generating the extratropical wave. Thus forecasters on the Gulf should watch the windfield over the Gulf of Mexico, preparatory to predicting the weather over the southern United States itself. This can be done by following waves in the easterlies westward from the Atlantic and the Caribbean, since such waves are among the systems that produce marked and rapid changes of the wind direction over the Gulf in summer.

4. Conclusions

Factors favorable for early transformation or dissipation of waves are the following:

a) Low value of zonal index (65°W to 95°W).

b) Predominately southerly rather than easterly flow in Gulf of Mexico.

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[14] 15-17 Aug 1930, 24-30 Aug 1934.

c) Deep pronounced troughs or fronts in the low latitudes in the central and western Caribbean.

Factors favorable for movement of waves far west before dissipation:

a) High zonal index of easterlies, and also of temperate latitude westerlies.

b) Arm of Bermuda high extending far west over northern Gulf of Mexico, with high located north and west of its position and predominately easterly rather than southerly flow in Gulf and western Caribbean.

c) Only weak, rapidly moving troughs passing to the north with polar lows displaced far to north.

SUMMARY OF CONCLUSIONS

Chapter I - Origin

1. The deep easterlies in themselves are not sufficient to form waves. Outside influences are essential for their generation.

2. Waves in the easterlies can originate in the east Atlantic in induced polar troughs extending equatorward from the Icelandic low.

3. Waves in the easterlies can originate in mid-Atlantic in a trough that has stagnated because of the blocking effect of a strong sub-tropical high to the east.

4. Waves in the easterlies do not form from polar troughs while the latter maintain their identity as separate and distinct stationary or eastward moving troughs in the tropics.

5. A position of the equatorial front north of its normal position in the east Atlantic often accompanies a wave in the easterlies in that region. Although no conclusive evidence is offered that this is a means of origin, the situation offers a good means of early identification.

Chapter II - Structure

1. The horizontal orientation is very nearly perpendicular to the mean wind flow between 1000 to 15,000 feet. The usual trough-line orientation being NNE-SSW.

2. The average slope of the wave is approximately 1:35.

3. Strong waves are still well marked at 40,000 feet. There is, however, an intermediate region between 20,000 and 35,000 feet where they are noticeably weaker.

4. The most pronounced windshifts with passage occur at 5000 to 15,000 feet and then again around 40,000 feet.

5. Most waves are preceded by 24-hour pressure falls of 1-2 mb at the surface and aloft, with subsequent rises of the same order of magnitude upon passage.

6. Shortly after passage, 24-hour temperature rises occur from the surface to approximately 8000 feet with 24-hour cooling above. Greater 24-hour cooling that extends to lower levels follows 12-24 hours after passage.

7. Before wave passage, the height of the top of the moist layer is approximately normal (12,000 feet). After passage, it rises to over 18,000 feet and attains the greatest height 12-24 hours after passage.

Chapter III - Weather Distribution

1. Fast-moving waves (>18 m.p.h.) are of weak intensity and have an approximately symmetrical distribution of weather about the wave trough.

2. Moderately moving waves (13 to 18 m.p.h.) are in general more intense than fast waves. The bad weather increases after wave passage.

3. Slow moving waves (<13 m.p.h.) are preceded by a pronounced zone of good weather and have maximum intensity of weather 12 hours after passage.

4. Decelerating waves (which develop into tropical storms) are the most intense of all types considered and gradually approach a nearly symmetrical distribution of weather about the wave trough.

Chapter IV - Maintenance

The following factors are favorable for maintenance and continued westward movement of waves in the easterlies:

1. Strong and deep easterlies, and a high value of the zonal index.

2. An oceanic high with pressure higher than normal.

3. Absence of temperate latitude systems, whose influence extends into the tropics.

4. An elongated high that covers the entire ocean or westward motion of the high cell situated to the north of a wave.

Chapter V - Displacement

1. Extrapolation at constant speed will yield good forecasting results if the pressure gradient north of the wave remains about constant.

   a) Deceleration should be forecast if the wave moves toward an area of lighter winds (normal to its troughline).

b) Acceleration should be forecast if the wave moves toward an area of stronger winds (normal to its troughline).

2. The wind velocity normal to a wave is a less reliable forecasting tool when applied alone than is extrapolation. If it is necessary to use it, however, the mean wind vector between 5,000 and 12,000 feet is recommended.

3. Computing displacement by use of a formula similar to Petterssen's proved unreliable.

Chapter VI - Intensification

1. Deceleration of waves is accompanied by intensification while acceleration is usually, but not necessarily, accompanied by dissipation.

2. Synoptic features, such as polar troughs, that tend to decelerate waves produce intensification provided they are not so deep as to destroy the easterly circulation of the tropics.

3. Closed low centers can be expected to form on waves in the areas of greatest cyclonic shear.

Chapter VII - Termination

1. Factors favorable for early transformation or dissipation of waves are the following:

   a) Low value of the zonal index (65°W to 95°W).

   b) Predominately southerly rather than easterly flow in Gulf of Mexico.

   c) Deep pronounced troughs or fronts in the low latitudes in the central and western Caribbean.

2. Factors favorable for movement of waves far west before dissipation.

   a) High zonal index -- both of easterlies and temperate latitude westerlies.

   b) Arm of Bermuda high extending far west over northern Gulf of Mexico, with high located north and west of its normal position and predominately easterly rather than southerly flow in Gulf and western Caribbean.

c) Only weak, rapidly-moving troughs passing to north, with polar lows displaced far to north.

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BAMS = Bull. Amer. Met. Soc.
QJRMS = Quart. Jn. Royal Met. Soc.

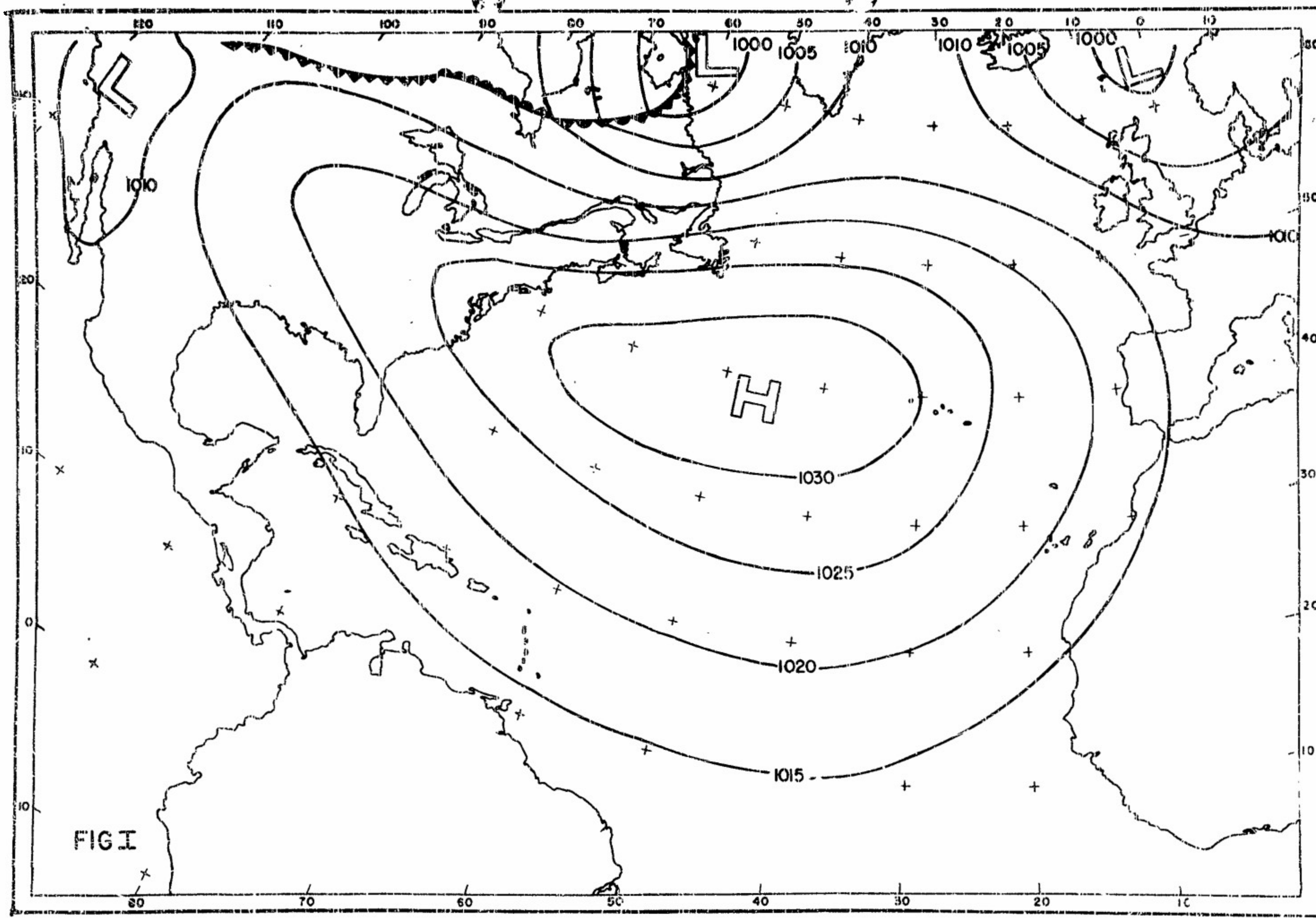
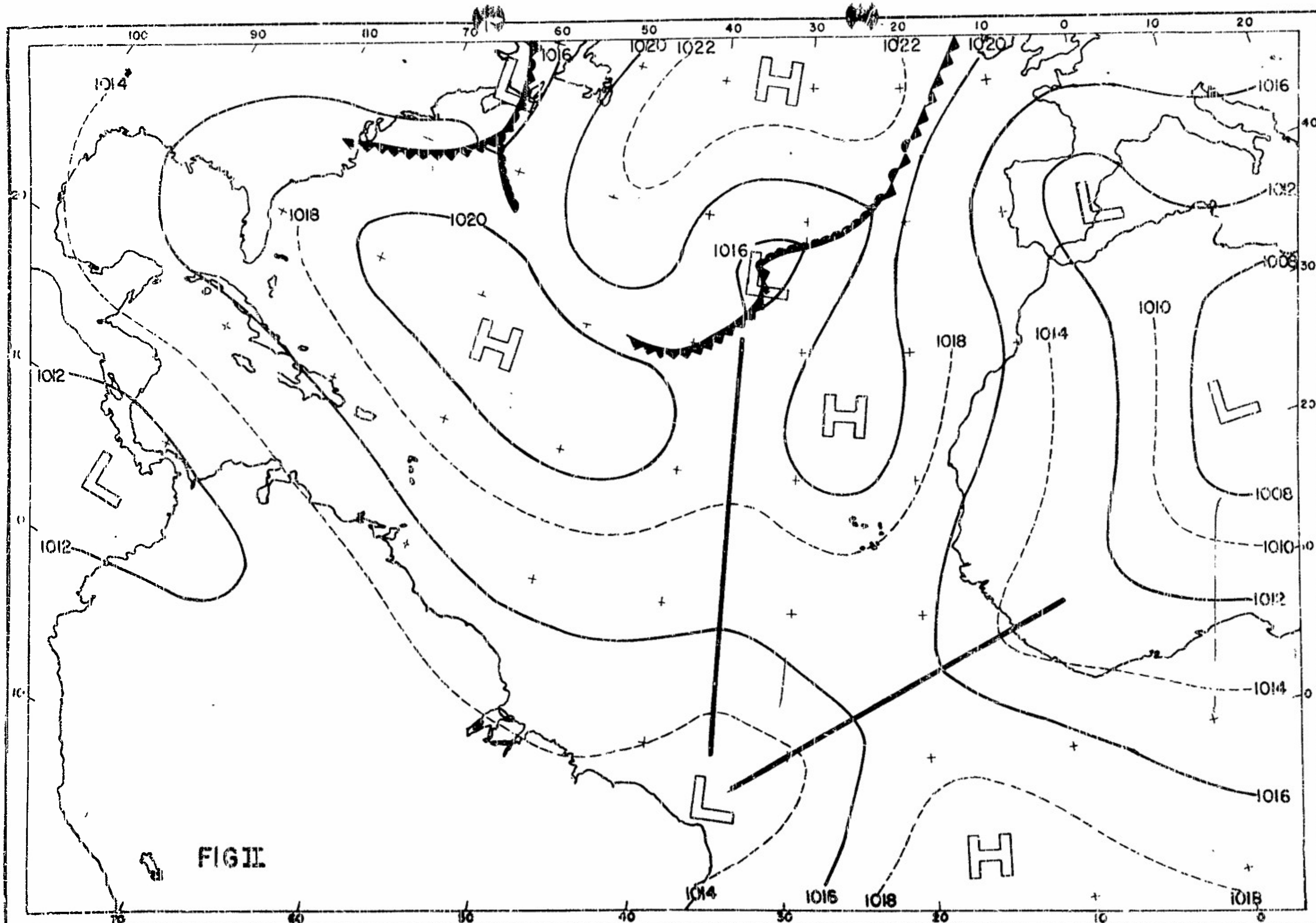


FIG I



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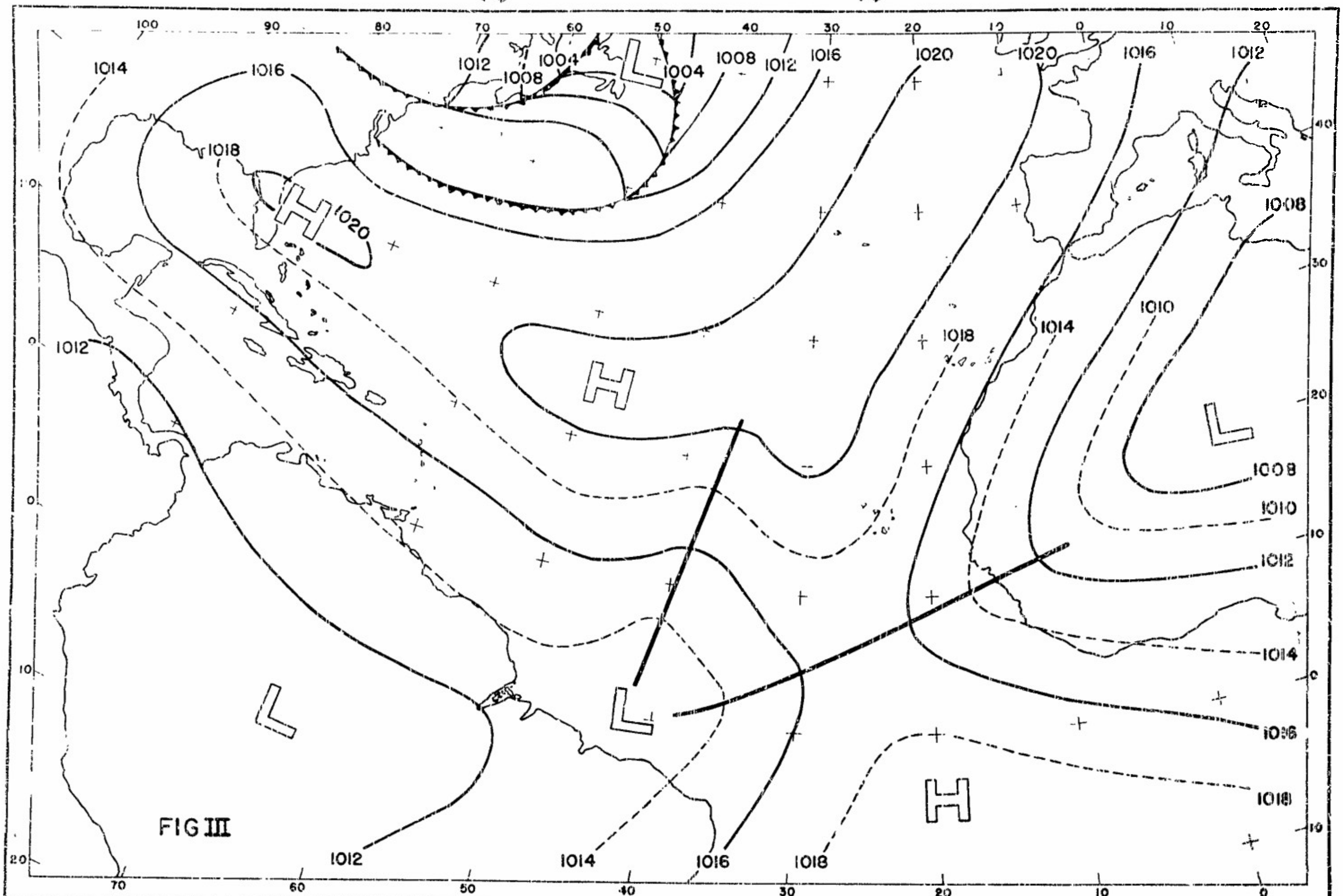

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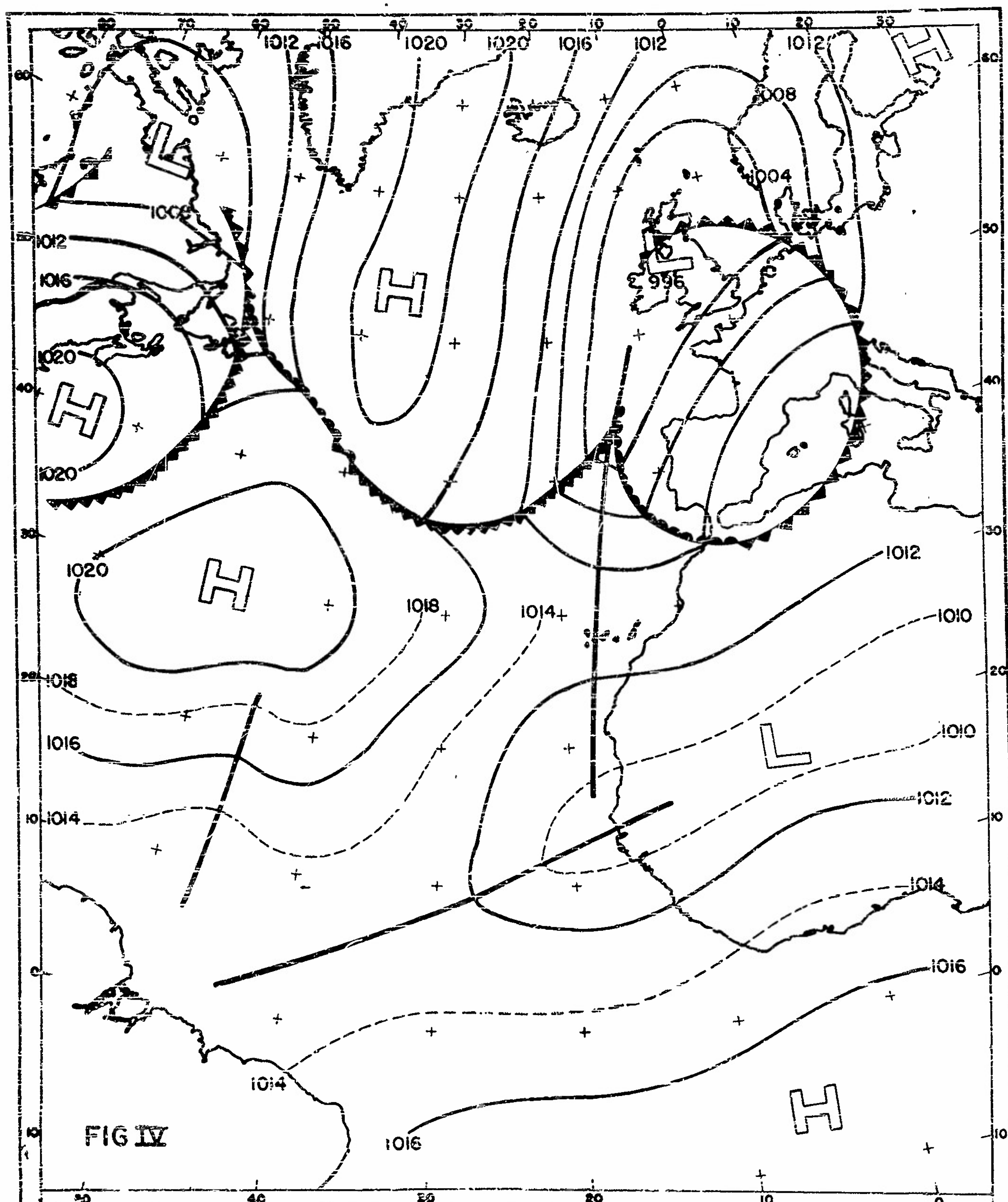
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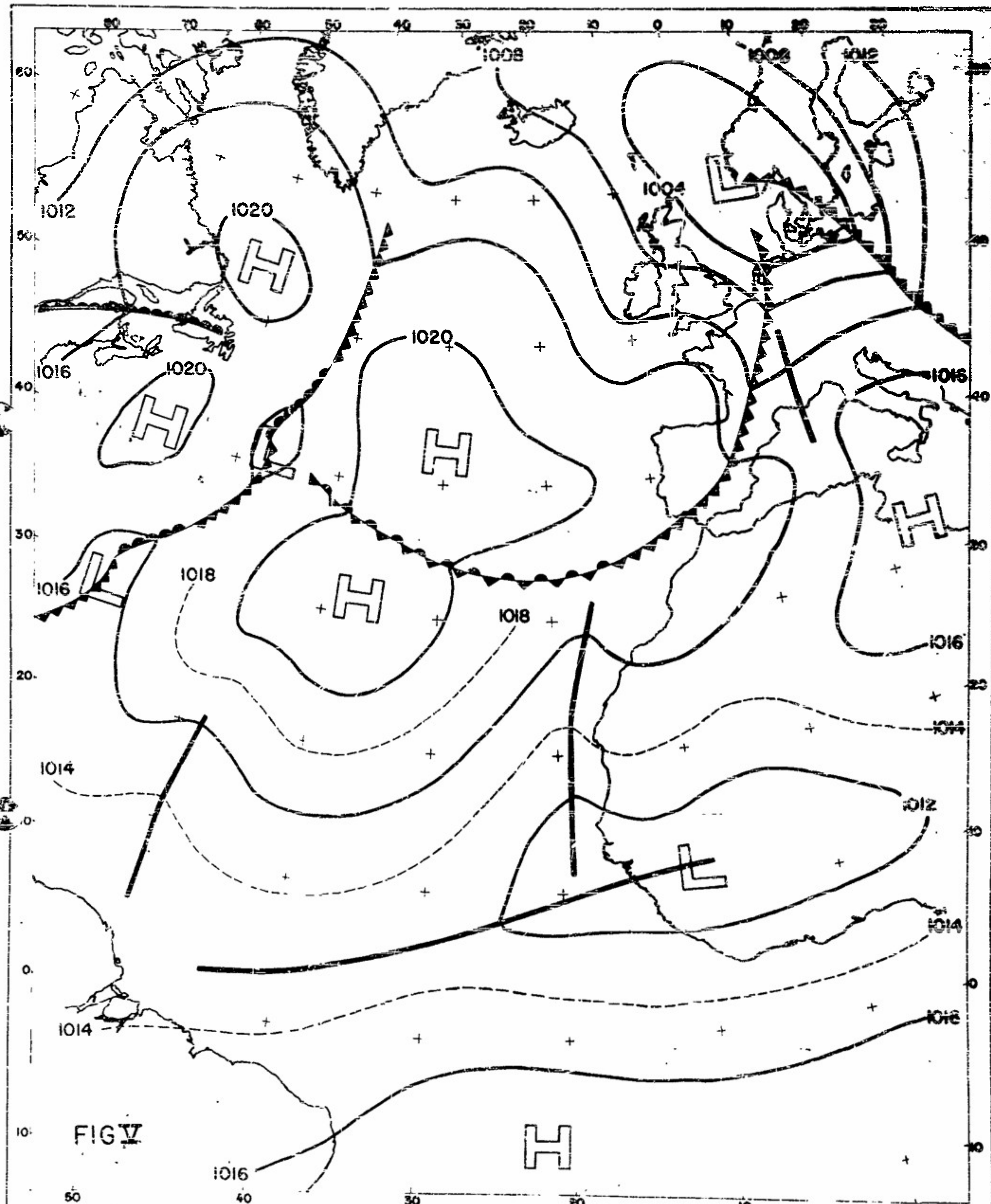
FIG IV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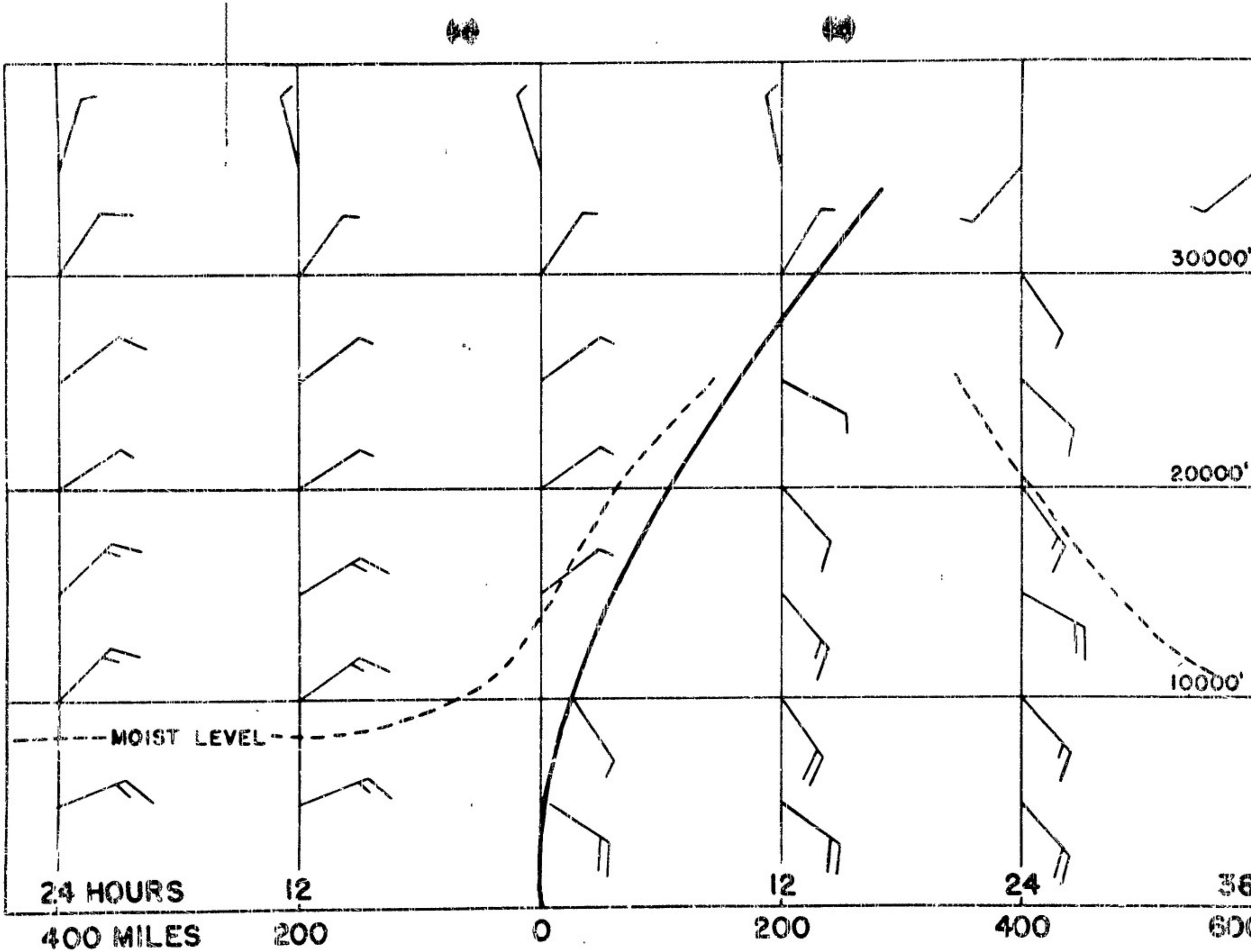

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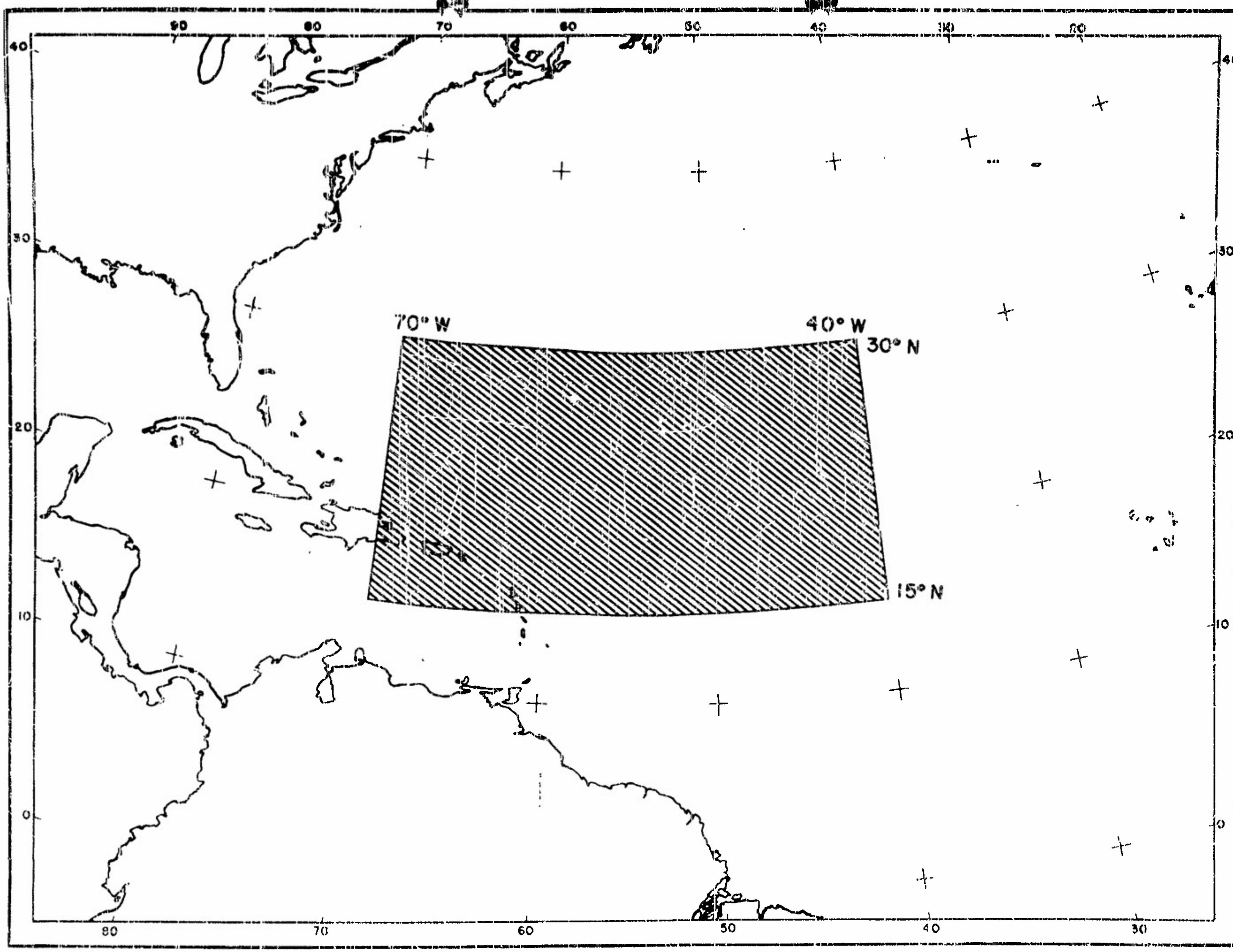
FIG VI



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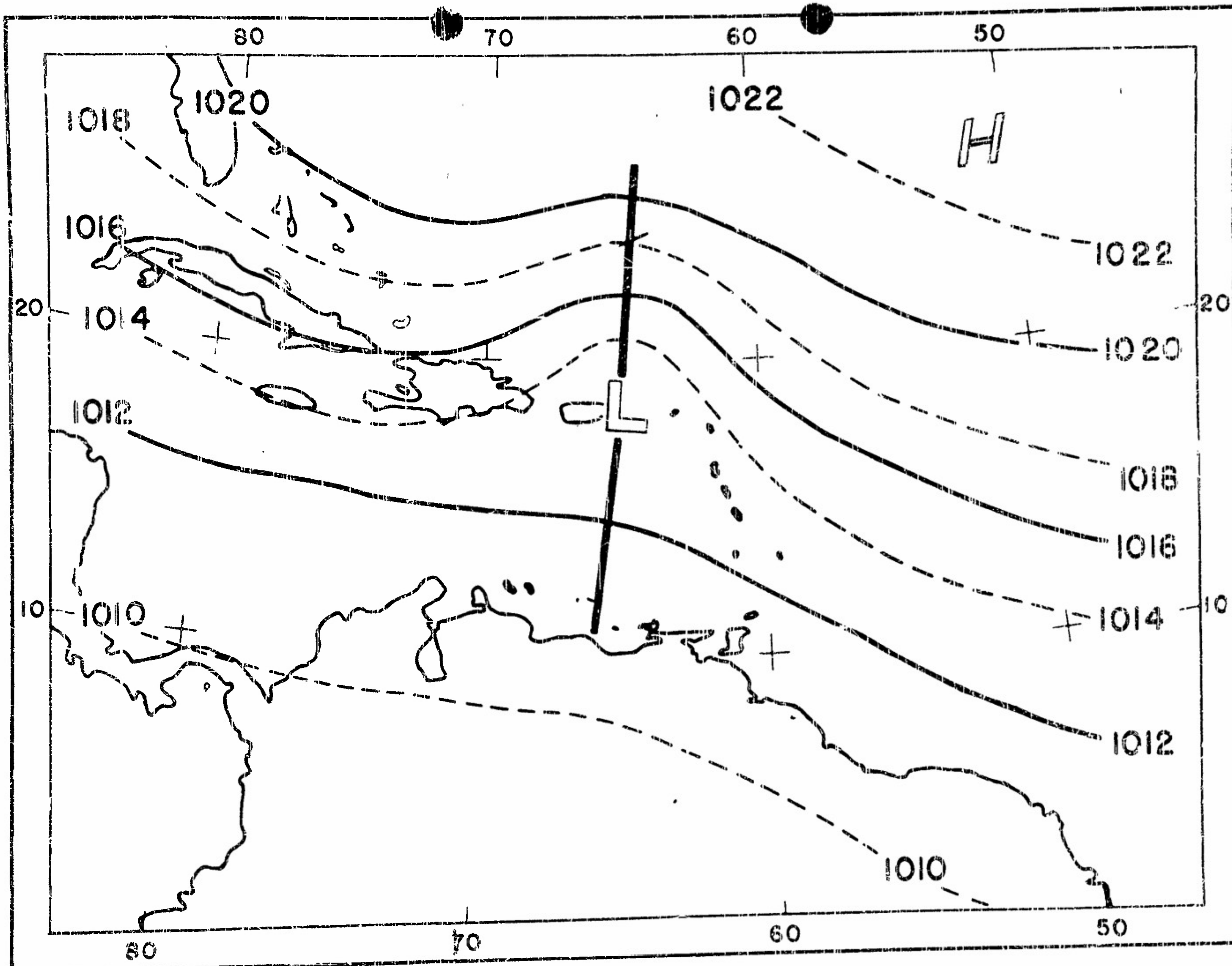
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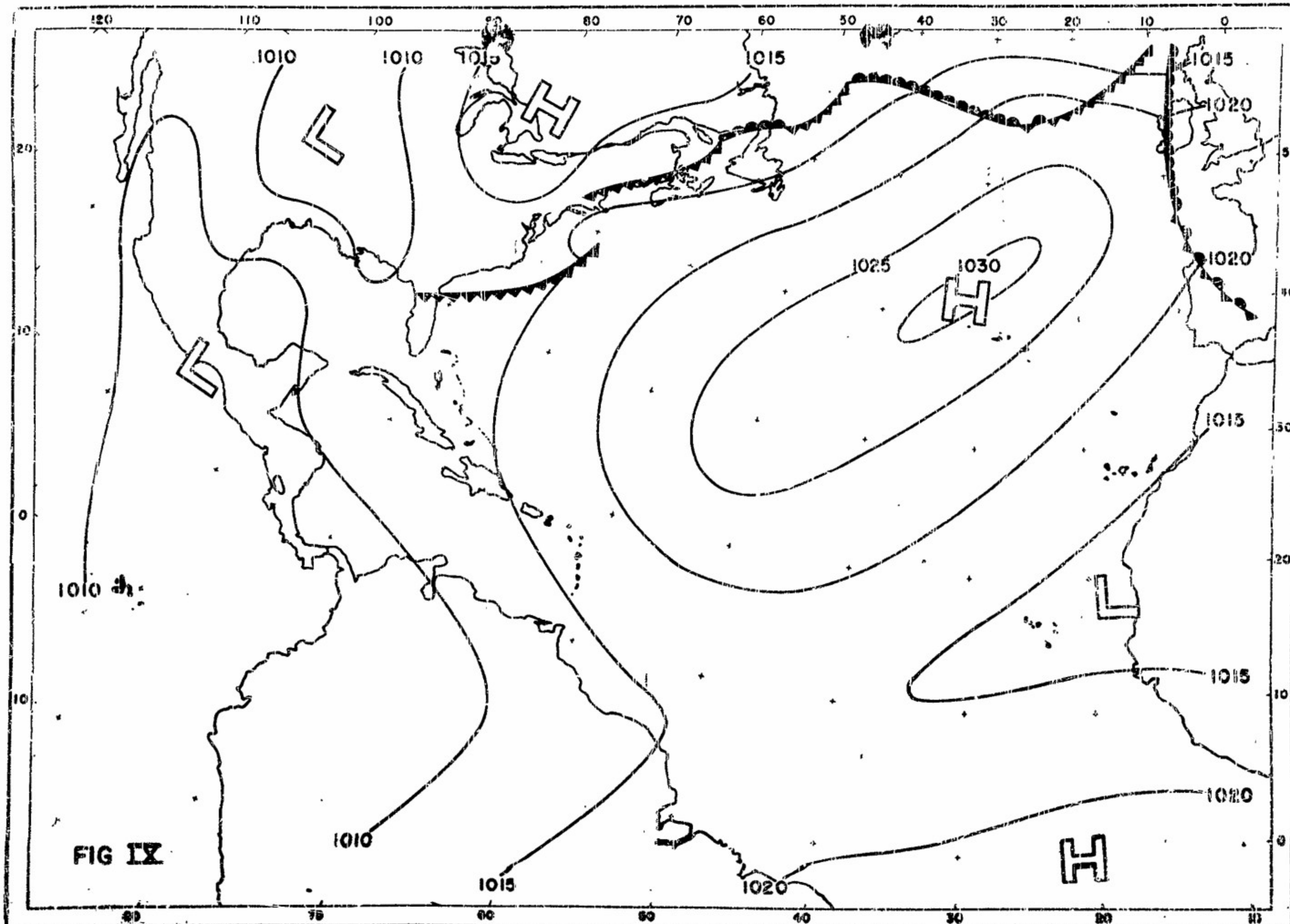
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FIG IX

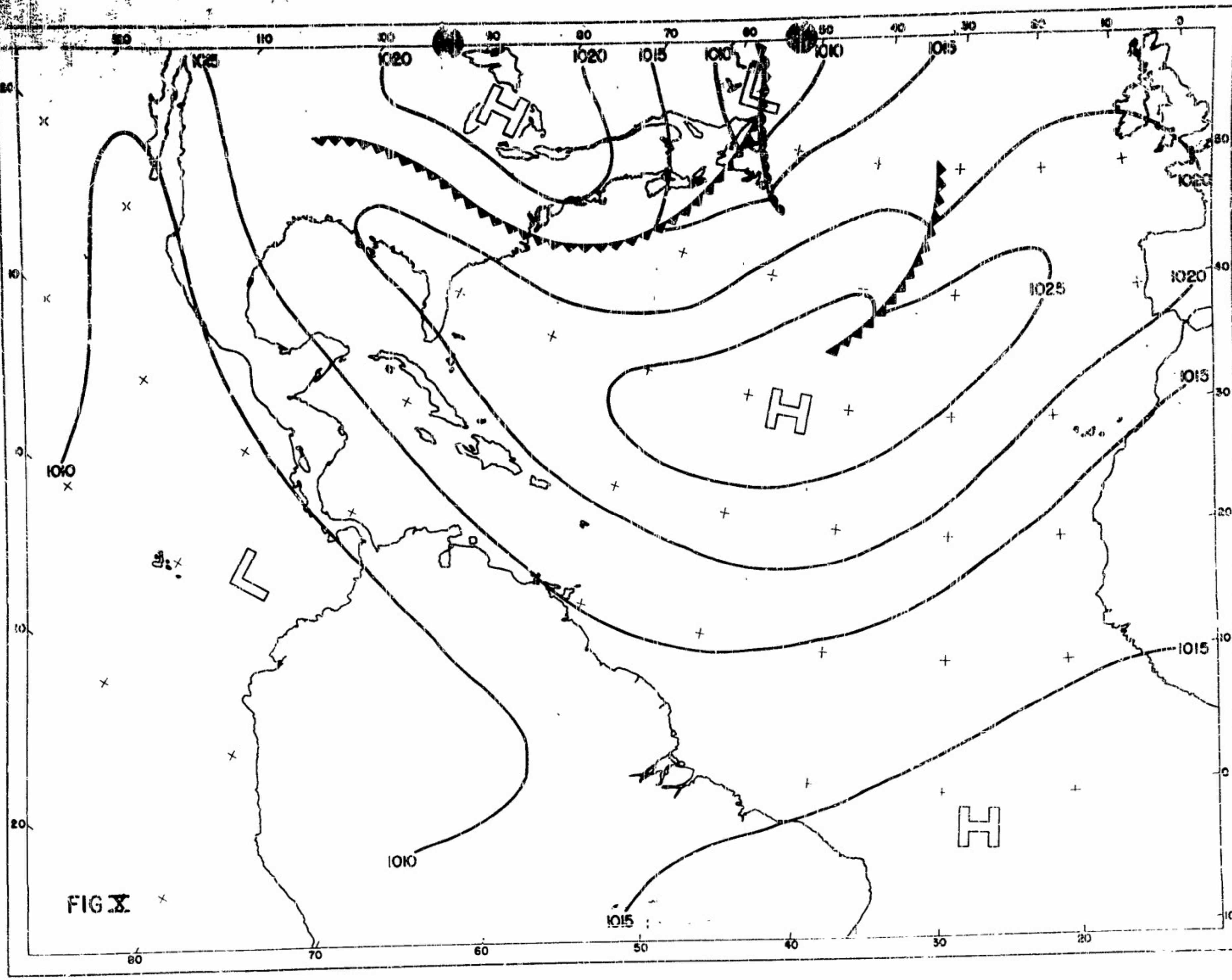
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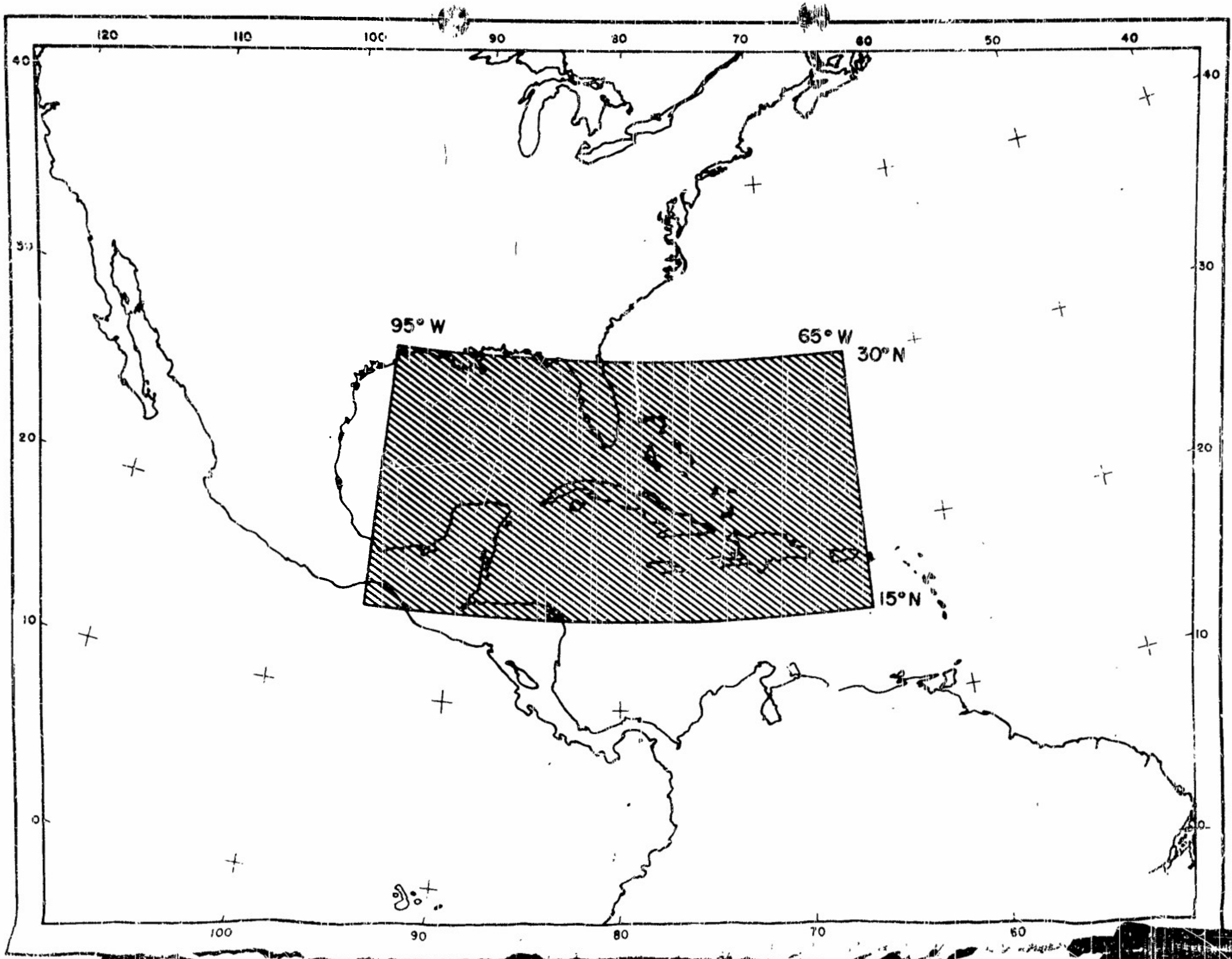
FIG X



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15° N